

# Lighting Calculations

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Lighting calculations are performed during the design process to obtain information about lighting system performance. A designer can use the results of calculations to choose between design alternatives or to refine a particular design. Lighting calculations are mathematical models of the complex physical processes that occur within a lighted space. Since these models can never be accurate in every detail, the computations are approximations of real situations.<sup>1</sup>

This chapter contains many of the fundamental calculation methods that are used in lighting system analysis, including both simple and complex methods. For methods that apply to specific applications, such as luminaire design, daylighting, floodlighting, roadway lighting, sports lighting, or merchandise lighting, see the special chapters for procedures particular to those areas.

The simplest lighting calculation methods can be performed by hand, whereas the more advanced methods can be performed only by using a computer. More advanced models generally provide more accurate information. Accuracy, for the purpose of this discussion, is defined as the degree to which the calculations agree with reality. In actuality, it is very difficult to achieve perfect agreement, as discussed later in this chapter.

Lighting calculation methods are application driven. The type of information that is desired about a lighting system and the complexity of the lighting condition being analyzed determine which calculation method is best applied to the problem. The aspects that must be evaluated in determining the lighting analysis model to use are the following:

- Information desired
- Equipment choice
- Equipment number and placement
- Space characteristics

It is the responsibility of the designer to determine and use the most appropriate calculation methods for an application. The material presented in this chapter provides the lighting practitioner with information that can be used in making these decisions.

This chapter provides general calculation procedures that are used in the analysis of direct and reflected light. In general, these are fundamental procedures that can be applied to all lighting analysis situations. Also included are specialized calculations commonly used in the evaluation of lighting systems. Finally, a set of example calculations is provided to illustrate the general algorithm for lighting calculations discussed in this chapter.

## BASIC PRINCIPLES

Predicting the radiative transport of luminous flux (or flux transfer) from a source to a receiving surface is fundamental to all lighting calculations. This transport is through air, which is assumed to be nonabsorbing and nonscattering.

Flux transfer is categorized into six types by geometry and emitter type:

1. Point source to a point or differential receiving area
2. Point source to a finite receiving area
3. Diffuse area source to a point or differential receiving area
4. Diffuse area source to a receiving area
5. Nondiffuse area source to a point or differential receiving area
6. Nondiffuse area source to a receiving area

Transfer type 1 is conceptually the simplest and is the easiest to formulate. Transfer types 2, 3, and 4 are obtained from the formulation of type 1 by integrating over the source, the receiving area, or both. Transfer types 5 and 6 are the most complicated, but they are also the most commonly encountered in practice. Light reaching a point or an area is described by *illuminance*, the measure of flux density or the incident flux per unit area.

It is often necessary to know how light reflects from a point or an area. Exitance is the simplest case and is measured as flux density leaving the surface. More complicated is *luminance*, which describes the flux leaving a surface in a particular direction. For exitance and luminance calculations the reflecting properties of the surface must be known. In these cases, methods for predicting illuminance are combined with reflectance information to predict exitances and luminances.

Photometric measurement of a luminaire provides a luminous intensity distribution from which the spatial distribution of flux from the luminaire is obtained. For calculations, the simplest cases are those in which the luminaire is small and can be considered a point. Flux transfer types 1 and 2 can be used. In many cases, the luminaires are large and flux transfer types 3 and 4 are required to provide adequate accuracy. Methods for assessing luminaire size are given below.

Interreflection is the multiple reflection of light among surfaces. It is an important aspect of most interior lighting systems, since it is by interreflection that many interior architectural surfaces acquire a luminance. It is by these luminances that architecture is also revealed and given perceptual form. For some interior lighting systems, interreflection is the only process by which the illuminance on the visual task is produced. Such is the case for indirect electric lighting and many daylighting systems.

## Direct Flux Transfer

**Flux Transfer Type 1, Point Source to a Point.** The illuminance  $E$  produced on an area  $A$  centered at a point  $P$  is related to the luminous intensity of a light source,  $I(\theta, \psi)$ , as follows. Given the intensity distribution of the light source in spherical coordinates  $(\theta, \psi)$ , the geometric arrangement is shown in [Figure 9-1](#).

The illuminance  $E$  is defined in terms of the flux  $\Phi$  incident on an area  $A$ :

$$E = \frac{\Phi}{A} \quad (9-1)$$

That flux can also be analyzed directionally in terms of the solid angle  $\omega$ . If the origin of a spherical coordinate system is located at the source, and the area  $A$  is small with respect to the distance  $D$ , then

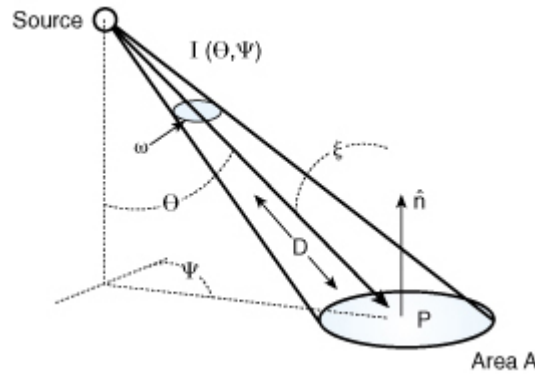
$$\omega = \frac{A}{D^2} \cos \xi \quad (9-2)$$

where

$D$  = distance between the source and point  $P$ ,

$\xi$  = angle between the normal ( $\hat{n}$ ) to the surface  $A$  and direction of the distance  $D$ .

The definition of the luminous intensity from the source is used to related Equations 9-2 and 9-1:



**Figure 9-1.** Geometric arrangement for the inverse square cosine law.

$$I(\theta, \psi) = \frac{\Phi}{\omega}$$

or

$$\Phi = I(\theta, \psi)\omega \quad (9-3)$$

Substituting this into Equation 9-1 gives

$$E = \frac{I(\theta, \psi)\omega}{A}$$

Substituting Equation 9-2 into this gives

$$E = \frac{I(\theta, \psi) \cos \xi}{D^2} \quad (9-4)$$

Equation 9-4 is the fundamental equation of flux transfer, the so-called inverse square cosine law.<sup>2</sup> Its validity assumes that of Equation 9-2 and that the luminous intensity is (nearly) constant in the neighborhood of the direction  $(\theta, \psi)$ .

As the area  $A$  (the neighborhood around point  $P$ ) is made smaller, the solid angle  $\omega$  becomes smaller and Equation 9-2 becomes more accurate. In the limit of a differential area,  $dA$ , the solid angle becomes differential,  $d\omega$ , and Equation 9-2 is exactly correct. The transfer of flux is conceptually equivalent to an infinitesimally narrow ray of light. The computational consequence of this consideration is that Equation 9-4 describes the illuminance at a differentially small neighborhood around point  $P$  or, more briefly, gives the illuminance at  $P$ .

Equation 9-2 expresses the solid angle subtended by the area  $A$  at a point; the light source is assumed to be coincident with this point. The computational consequence is that Equation 9-4 describes the illuminance from a point source.

The intensity value used in Equation 9-4 is most often obtained by interpolation from values in a table. Intensity distributions are almost always expressed using the two angles of spherical coordinates; thus the required interpolation is over these two angles. Bilinear splines, bicubic splines, and double Fourier series are among the methods used.<sup>3,4</sup>

#### Flux Transfer Type 2, Point Source to a Receiving Area.

The flux transferred from a point source to a differential area can be expressed using Equation 9-4. This is integrated over the receiving area to give the flux received by the entire area:

$$\begin{aligned} d\Phi &= EdA \\ \Phi &= \int EdA \\ \Phi &= \int \frac{I(\theta, \psi) \cos \xi}{D^2} dA \end{aligned} \quad (9-5)$$

The integration is over the receiving area  $A$ .

Equation 9-5 can alternatively be solved using Monte Carlo integration.<sup>5-7</sup> Conceptually, light rays are traced from the point source  $P$  to randomly selected points on the receiving area,  $A$ , with Equation 9-4 being evaluated for each ray. Assuming a random distribution of  $n$  points on  $A$ , the flux received by  $A$  is approximately:

$$\Phi = \sum_{i=1}^n \frac{E_i A}{n}$$

where  $E_i$  is the illuminance of  $A$  at the receiving point due to ray  $i$ . The accuracy of the solution improves with increasing  $n$ .

Analytic integration of Equation 9-5 is possible only if the intensity distribution is a simple function and the geometric arrangement is simple.<sup>3</sup> Otherwise it is necessary to approximate the area integral of Equation 9-5 with a finite sum. In this case the receiving surface is broken up into small areas, or discretized, and Equation 9-4 is applied to each. The smaller and more numerous the  $n$  discrete areas, the more accurate the result:

$$\Phi = \sum_{i=1}^n I(\theta_i, \psi_i) \cos \xi_i \frac{a_i}{D_i^2} \quad (9-6)$$

where

$I(\theta_i, \psi_i)$  = intensity of the point source in the direction of the  $i$ th piece of area  $A$ ,  
 $\xi_i$  = incident angle at the  $i$ th piece of area  $A$ ,

$a_i$  = area of the  $i$ th piece of area  $A$ ,

$D_i$  = distance between the source and the  $i$ th piece of area  $A$ .

The average illuminance,  $\bar{E}$ , can be obtained from either Equation 9-5 or 9-6:

$$\bar{E} = \frac{\Phi}{A}$$

**Flux Transfer Type 3, Diffuse Area Source to a Point.** In many applications the light source is too large, or the point at which the illuminance is to be calculated is too close, for the conditions of validity for direct use of Equation 9-4 to be met. However, if the source is a diffuse emitter, Equation 9-4 can be used indirectly.

The intensity distribution of a diffuse emitter, in spherical coordinates, is given by

$$I(\theta, \psi) = I_n \cos \theta$$

The distribution is axially symmetric about the direction (0,0), which is also the surface normal (perpendicular).  $I_n$  is the luminous intensity in the direction of the surface normal.

Because each differential element  $dA$  of the source is a diffuse emitter, the intensity distribution of such an element is

$$dI(\theta, \psi) = \frac{M_{dA} \cos \theta}{\pi} dA$$

where  $M_{dA}$  is the exitance of the source at the differential element  $dA$ . The illuminance produced at the point  $P$  is

$$dE = \frac{M_{dA} \cos \theta \cos \xi}{\pi D^2} dA$$

and the illuminance produced by the entire source is

$$E = \frac{1}{\pi} \int \frac{M_{dA} \cos \theta \cos \xi}{D^2} dA \quad (9-7)$$

If the source exhibits a constant exitance  $M$  over its extent, then

$$E = \frac{M}{\pi} \int \frac{\cos \theta \cos \xi}{D^2} dA \quad (9-8)$$

The integration is over the extent of the source.

The quantity that multiplies the exitance  $M$  is purely geometric and is called the configuration factor,  $c$ .<sup>8</sup> More simply,

$$E = Mc \quad (9-9)$$

where

$$c = \frac{1}{\pi} \int \frac{\cos \theta \cos \xi}{D^2} dA \quad (9-10)$$

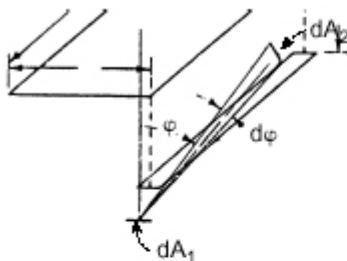
The configuration factor relates the exitance of a diffuse area emitter to the illuminance it produces at a point. It has the limiting values

$$0 \leq c \leq 1$$

Alternative definitions of the configuration factor are possible. It can be defined as that fraction of the total flux emitted by a differential diffuse emitter that is received directly by an area. The analytic result of this definition is Equation 9-10. This configuration factor has been evaluated for a large number of geometric conditions.<sup>9</sup> A selection of these equations is given in [Figures 9-2](#) and 9-3.

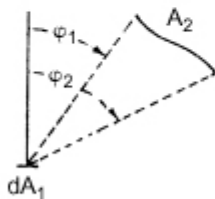
Equation 9-10 assumes that there are no intervening objects between the diffuse area source  $A$  and the point receiver  $P$ . If there are, then Equation 9-10 becomes:

$$c = \frac{1}{\pi} \int \frac{V(\theta, \xi) \cos \theta \cos \xi}{D^2} dA$$



Area  $dA_1$  of differential width and any length strip  $dA_2$  of differential width and with generating line to  $dA_1$ .

$$c = \frac{\cos \phi}{2} d\phi$$

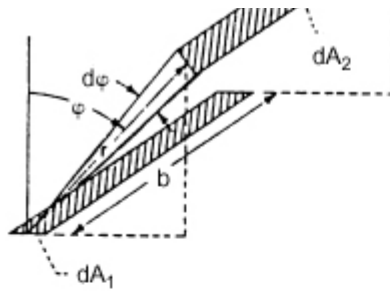


Area  $dA_1$  of differential width and any length cylindrical surface  $A_2$  generated by a line moving parallel to itself and parallel to the

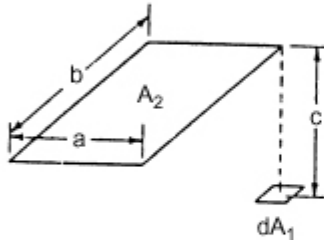
$$c = \frac{1}{2} (\sin \phi_2 - \sin \phi_1)$$



Strip  $A_1$  of length  $b$  and differential width strip  $dA_2$  of same length on parallel gener

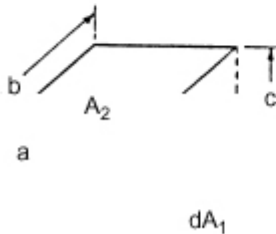


$$C = \frac{\cos \phi}{\pi} d\phi \arctan \frac{Y}{X}$$



Plane element  $dA_1$  to plane parallel rectangular area  $A_2$  passes through corner of rectangle.  $Y = b/c$ .

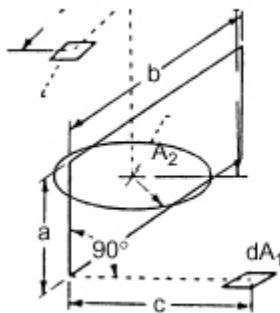
$$C = \frac{1}{2\pi} \left( \frac{X}{\sqrt{1+X^2}} \arctan \frac{Y}{\sqrt{1+X^2}} + \frac{Y}{\sqrt{1+Y^2}} \arctan \frac{X}{\sqrt{1+Y^2}} \right)$$



Strip element  $dA_1$  to rectangle  $A_2$  in plane. Strip is opposite one edge of rectangle.  $X = a/b$ .

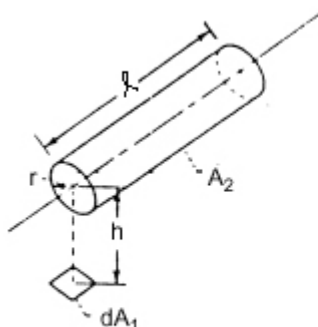
$$C = \frac{1}{\pi Y} \left[ \sqrt{1+Y^2} \arctan \frac{X}{\sqrt{1+Y^2}} - \frac{XY}{\sqrt{1+X^2}} \arctan \frac{Y}{\sqrt{1+X^2}} \right]$$

Figure 9-2. Continued



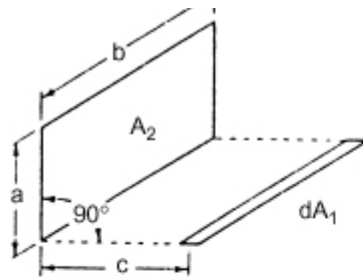
Plane element  $dA_1$  to rectangle  $A_2$  in plane.  $X = a/b$ ;  $Y = c/b$ .

$$C = \frac{1}{2\pi} \left[ \arctan \frac{1}{Y} - \frac{Y}{\sqrt{X^2+Y^2}} \arctan \frac{X}{Y} \right]$$



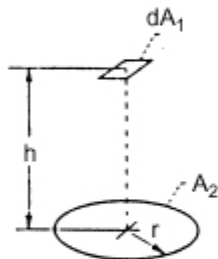
Plane element  $dA_1$  to right circular cylinder of length  $l$  and radius  $r$ ; normal to element passes through one end of cylinder and is perpendicular to axis.  $L = l/r$ ;  $H = h/r$ ;  $X = (1 + H^2) + L^2$ .

$$C = \frac{1}{\pi H} \arctan \frac{L}{\sqrt{H^2+1}} + \frac{L}{\pi} \left[ \frac{(X-2H)}{H\sqrt{XY}} \arctan \sqrt{\frac{X(H-1)}{Y(H-1)}} - \frac{1}{\sqrt{X^2+Y^2}} \arctan \frac{X}{Y} \right]$$



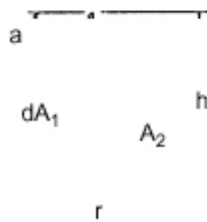
Strip element  $dA_1$  to rectangle  $A_2$  in plane;  $X = a/b$ ;  $Y = c/b$ .

$$C = \frac{1}{\pi} \left\{ \arctan \frac{1}{Y} + \frac{Y}{2} \ln \left[ \frac{Y^2 (1 + \sqrt{X^2 + Y^2})}{(Y^2 + 1)} \right] - \frac{Y}{\sqrt{X^2 + Y^2}} \arctan \frac{1}{\sqrt{X^2 + Y^2}} \right\}$$



Plane element  $dA_1$  to circular disk  $A_2$  in plane; normal to element passes through center of disk.

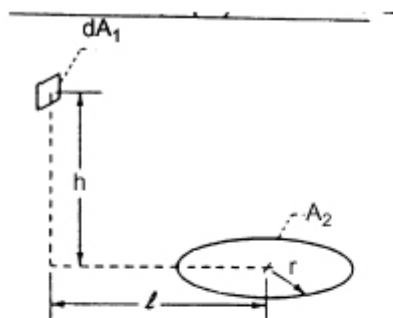
$$C = \frac{r^2}{h^2 + r^2}$$



Plane element  $dA_1$  to circular disk  $A_2$  in plane;  $H = h/a$ ;  $R = r/a$ ;  $Z = 1 + H^2$ .

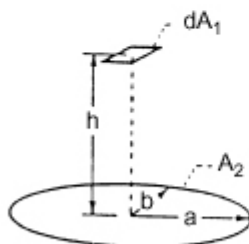
$$C = \frac{1}{2} \left( 1 - \frac{1 + H^2}{\sqrt{Z^2 - 4R^2}} \right)$$

Figure 9-2. *Continued*



Plane element  $dA_1$  to circular disk  $A_2$ ; element and disk intersect at  $90^\circ$ ;  $H = h/a$ ;  $R = r/a$ ;  $Z = 1 + H^2 + R^2$ .

$$C = \frac{H}{2} \left( \frac{Z}{\sqrt{Z^2 - 4R^2}} \right)$$



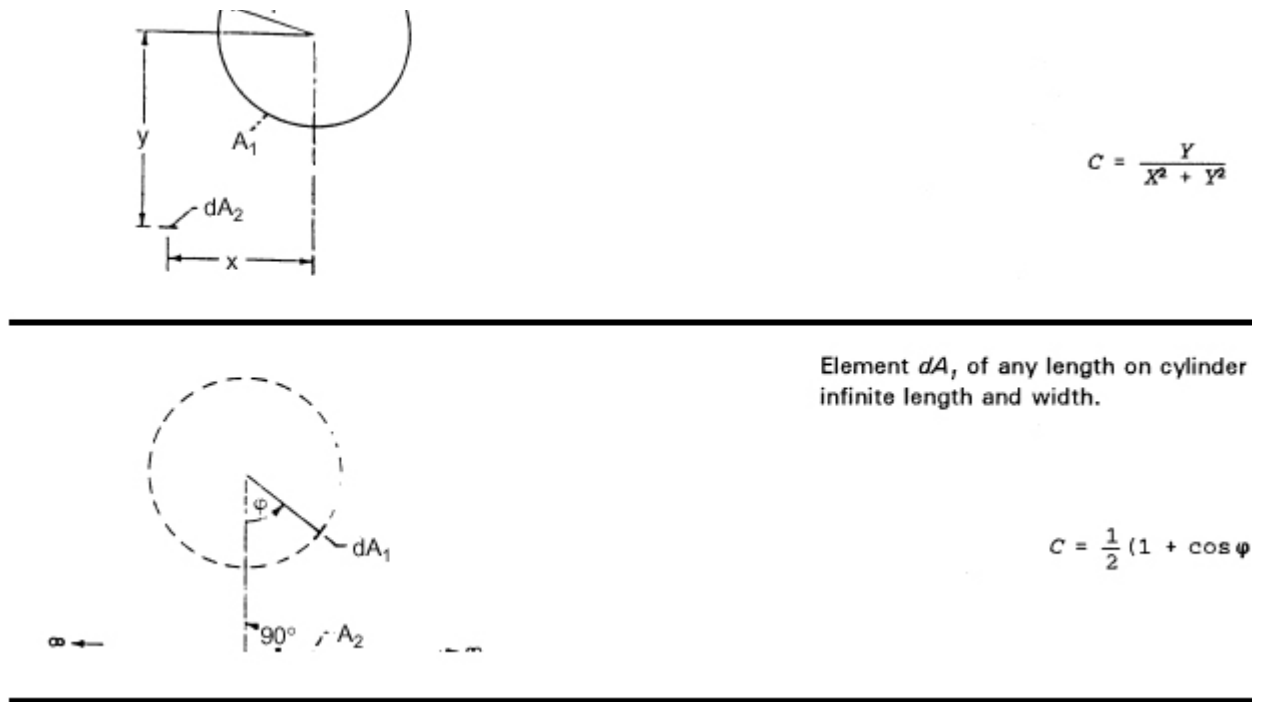
Plane element  $dA_1$  to elliptical plate  $A_2$  in plane; normal to element passes through center of plate.

$$C = \frac{ab}{\sqrt{(h^2 + a^2)(h^2 + b^2)}}$$



Strip element  $dA_2$  of any length to infinite plate  $A_1$ ;  $X = x/r$ ;  $Y = y/r$ .





**Figure 9-2.** Configuration factors ( $C$ ) for diffuse line and area sources.

where the visibility term  $V(\theta, \xi)$  is 1 if  $P$  is visible from  $dA$  and 0 if it is hidden by an intervening object. In complex environments such as rooms with partitions and furniture, it is often necessary to solve this equation using numerical integration methods such as the hemicube method<sup>5-7</sup> or quasi-Monte Carlo ray casting.<sup>7</sup> Both approaches are based on Nusselt's analogy (Figure 9-4), where the configuration factor  $c$  is equal to the area of the double projection of  $A$  onto the base of the hemisphere, divided by the area of the base.

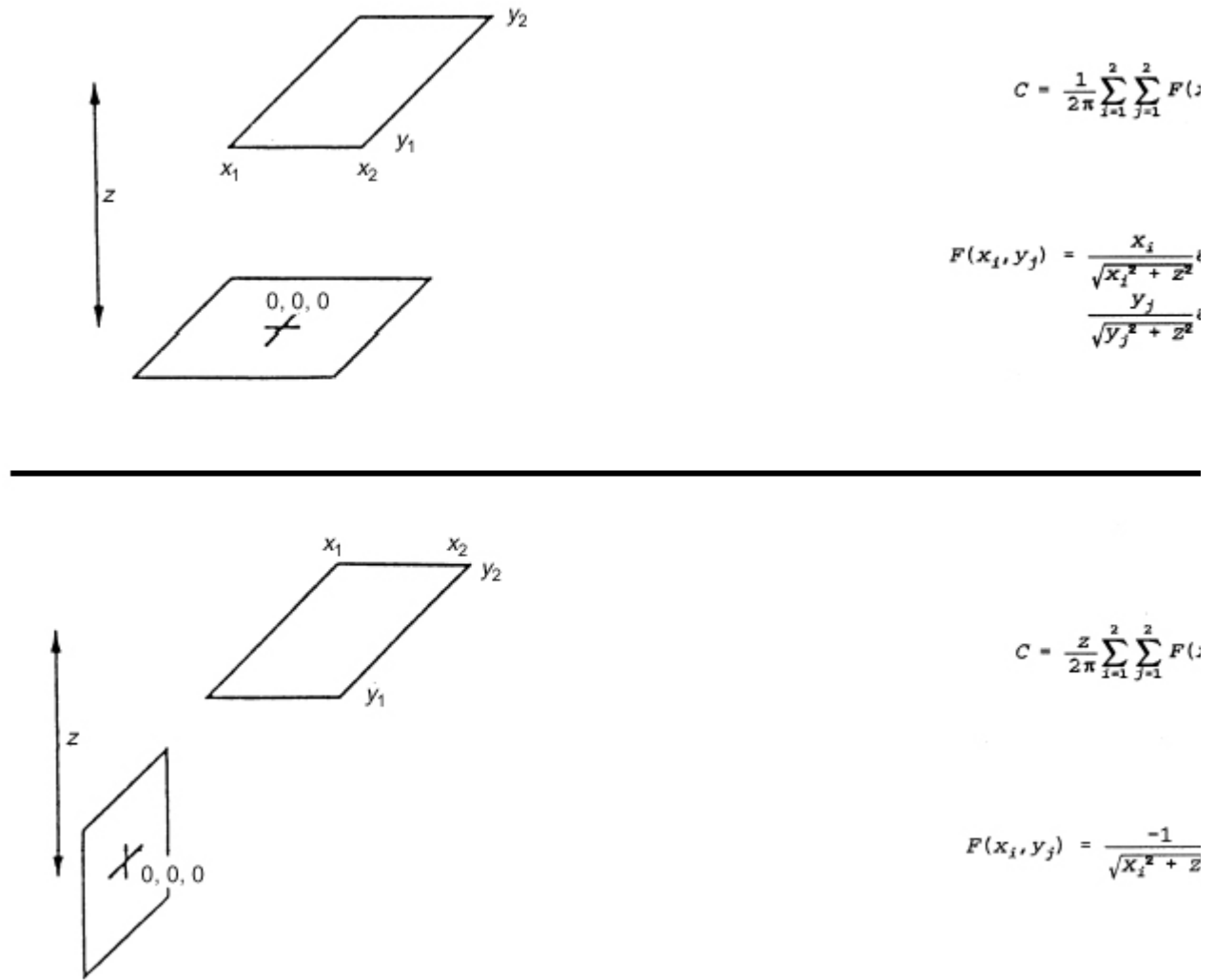
Equation 9-9 can be used to calculate the illuminance at a point produced by any diffuse emitter having a shape for which the configuration factor is known or can be calculated. Note that the emitter is assumed to have a uniform diffuse exitance.

**Flux Transfer Type 4, Diffuse Area Source to a Receiving Area.** If the emitting surface is specified as  $A_1$  and the receiving surface as  $A_2$ , then the flux sent from  $A_1$  to  $A_2$ , or  $\Phi_2$ , is

$$\Phi_2 = \int E_{dA_2} dA_2$$

where  $E_{dA_2}$  is the illuminance at element  $dA_2$  from all of source  $A_1$ . Substituting for  $E_{dA_2}$  using Equation 9-7 gives

$$\Phi_2 = \int \frac{1}{\pi} \int \frac{M_{1dA_1} \cos \theta \cos \xi}{D^2} dA_1 dA_2$$



**Figure 9-3.** General configuration factors ( $C$ ) for parallel and perpendicular rectangles.

If the source exhibits a constant exitance  $M_1$  over its extent, then

$$\Phi_2 = \frac{M_1}{\pi} \iint \frac{\cos \theta \cos \xi}{D^2} dA_1 dA_2 \quad (9-11)$$

The integration is over the extent of the source and the extent of the illuminated area. The quantity that multiplies the exitance  $M_1$  is purely geometric. It is customary to divide it by the area  $A_1$  so that it is the fraction of flux leaving surface  $A_1$  that reaches  $A_2$ . This is called the form factor  $f_{1 \rightarrow 2}$ .<sup>8</sup> Subscripts for form factors are necessary to indicate the direction in which flux is transferred. We have

$$f_{1 \rightarrow 2} = \frac{1}{\pi A_1} \iint \frac{\cos \theta \cos \xi}{D^2} dA_1 dA_2 \quad (9-12)$$

With this definition, Equation 9-11 becomes

$$\Phi_2 = M_1 A_1 f_{1 \rightarrow 2}$$

The average illuminance,  $\bar{E}_2$ , produced on surface  $A_2$  is then

$$\bar{E}_2 = \frac{\text{flux emitted by } A_1 \text{ reaching } A_2}{A_2}$$

$$\bar{E}_2 = \frac{M_1 A_1 f_{1 \rightarrow 2}}{A_2}$$

Form factors and areas relate the exitance of a diffuse area emitter to the average illuminance produced on a receiving surface. The form factors have the limiting values

$$0 \leq f \leq 1$$

and exhibit reciprocity:

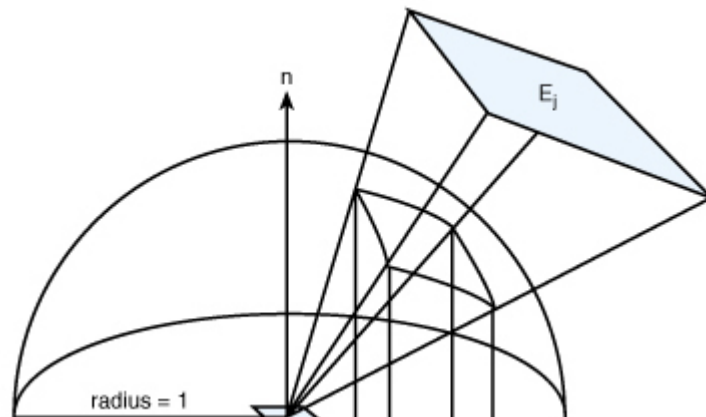
$$A_1 f_{1 \rightarrow 2} = A_2 f_{2 \rightarrow 1}$$

Application of reciprocity gives

$$\bar{E}_2 = M_1 f_{2 \rightarrow 1} \quad (9-13)$$

The equation for the form factor has been evaluated for a large number of geometric conditions. A selection of these equations is given in [Figures 9-5](#) and 9-6.

Equations 9-9 and 9-13 have wide application for the calculation of illuminance and average illuminance produced by any form of diffuse emitter. Most large architectural surfaces exhibit a diffuse reflectance and therefore are diffuse emitters by reflection. The illuminance produced by such surfaces can be calculated using Equations 9-9 and 9-13. This includes surfaces made luminous by interreflection of light and indirectly lighted surfaces.





**Figure 9-4.** Construction of Nusselt's analogy for diffuse radiative transfer from a point to an area.

It is difficult to analytically evaluate the form factor between two areas with arbitrary geometry, and even more difficult in the presence of occluding objects.<sup>10,11</sup> Approximate evaluations can be obtained using Monte Carlo ray casting.<sup>6,7</sup>

Skylights and windows are commonly approximated as diffuse emitters by reason of the type of transmittance they exhibit. Equations 9-9 and 9-13 can be used in these cases also.

If an area diffuse emitter does not have a uniform exitance, it can be discretized into smaller elements, each of which has a nearly uniform exitance. The illuminance produced by each element is then calculated by repeated application of Equation 9-9 or 9-13. The total effect is obtained by adding the individual illuminances.

**Flux Transfer Type 5, Nondiffuse Area Source to a Point.** Nondiffuse area emitters are significantly more difficult to treat than diffuse emitters. If a far-field intensity distribution is available for the luminaire, Equation 9-4 can be used in certain cases. If the distance from the luminaire to the calculation point is greater than five times the largest dimension of the luminaire, then treating the luminaire as a point source using Equation 9-4 gives a computational accuracy of approximately 5% or better.

For points closer to the luminaire, an assumption can be made about homogeneity (surface uniformity) that permits a useful approximation to be made.<sup>3</sup> Under this assumption, the intensity distribution of any differential element of the emitter,  $dI(\theta, \psi)$ , is proportional to the intensity distribution,  $I(\theta, \psi)$ , of the entire luminaire. The constant of proportionality is the ratio of the area  $dA$  of the differential element to the area  $A$  of the entire luminaire. That is,

$$dI(\theta, \psi) = I(\theta, \psi) \frac{dA}{A}$$

The differential element is then treated as a point source, and Equation 9-4 is used to express the differential illuminance it produces:

$$dE = \frac{dI(\theta, \psi) \cos \xi}{D^2} = \frac{1}{A} \frac{I(\theta, \psi) \cos \xi}{D^2} dA$$

Integration over the surface of the luminaire gives

$$E = \frac{1}{A} \int \frac{I(\theta, \psi) \cos \xi}{D^2} dA \quad (9-14)$$

Analytic integration of Equation 9-14 is possible only if the intensity distribution is a simple function and the geometric arrangement is simple. Otherwise it is necessary to approximate the area integral of Equation 9-14 with a finite sum. In this case, the luminaire is discretized into small areas. The smaller and more numerous the discrete areas, the more accurate the result:

$$E = \frac{1}{A} \sum_i I(\theta_i, \psi_i) \cos \xi_i \frac{a_i}{D_i^2} \quad (9-15)$$

where the summation is over all the discrete pieces of the luminaire, and

$I(\theta_i, \psi_i)$  = intensity of the  $i$ th piece of the luminaire surface to point  $P$ ,

$\xi_i$  = incident angle for flux from the  $i$ th piece of the luminaire surface,

$a_i$  = area of the  $i$ th piece of the luminaire surface,

$D_i$  = distance between the  $i$ th piece of the luminaire surface and point  $P$ ,

$A$  = area of the luminaire surface.

Equation 9-15 has wide application for the calculation of illuminance produced by luminaires with nondiffuse distributions.

**Flux Transfer Type 6, Nondiffuse Area Source to a Receiving Area.** If the nondiffuse emitting surface is specified as  $A_1$  and the receiving surface as  $A_2$ , then the flux  $\Phi_2$  sent from  $A_1$  to  $A_2$  is

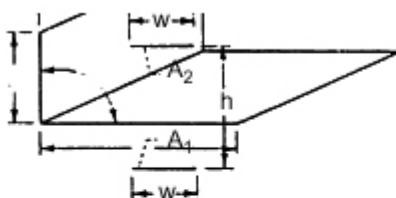
$$\Phi_2 = \int E_{dA_2} dA_2$$

where  $E_{dA_2}$  is the illuminance at element  $dA_2$  from all of source  $A_1$ .

Under the same assumption of luminaire homogeneity described above, Equation 9-14 can be used to express  $E_2$ :

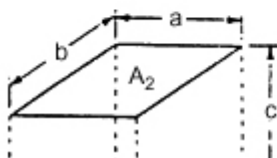
$$E_2 = \int \frac{1}{A_2} \int \frac{I(\theta, \psi) \cos \xi}{D^2} dA_1 dA_2 \quad (9-16)$$

The double area integrals usually cannot be evaluated analytically, and a double area summation is used as an approximation. In this case the luminaire and the receiving surface are discretized into small areas. The smaller and more numerous the discrete areas, the more accurate the result:



Two infinitely long, directly opposed plates same finite width.  $H = h/w$ .

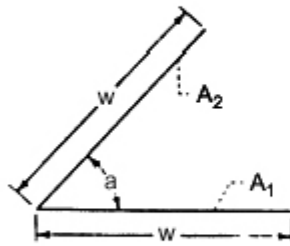
$$F_{1-2} = F_{2-1} = \sqrt{1 + H^2} - 1$$



Identical, parallel, directly opposed rectangles.  $X = a/c$ ;  $Y = b/c$ .

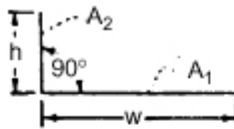


$$F_{1-2} = \frac{2}{\pi XY} \left( \ln \left[ \frac{(1+X^2)(1+Y^2)}{1+X^2+Y^2} \right]^{1/2} + X\sqrt{1+Y^2} + Y\sqrt{1+X^2} \arctan \frac{Y}{\sqrt{1+X^2}} - X \arctan X \right)$$



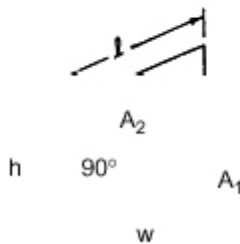
Two infinitely long plates  $A_1$  and  $A_2$  of equal width  $W$ , having one common edge, and at an included angle  $\alpha$ .

$$F_{1-2} = F_{2-1} = 1 - \sin \frac{\alpha}{2}$$



Two infinitely long plates  $A_1$  and  $A_2$  of unequal width  $W$  and height  $H$ , having one common edge, and at an angle of  $90^\circ$  to each other.  $H = h/w$ .

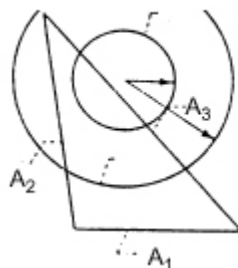
$$F_{1-2} = \frac{1}{2} [1 + H - \sqrt{1+H^2}]$$



Two finite rectangles  $A_1$  and  $A_2$  of same length  $l$ , having one common edge, and at an angle of  $90^\circ$  to each other.  $H = h/l$ ;  $W = w/l$ .

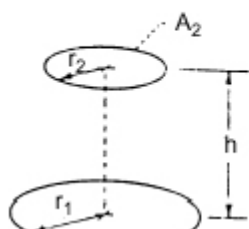
$$F_{1-2} = \frac{1}{\pi W} \left( W \arctan \frac{1}{W} + H \arctan \frac{1}{H} - \sqrt{H^2 + 1} \right) + \frac{1}{4} \ln \left[ \frac{(1+H^2)(1+W^2)}{(1+H^2+W^2)} \right] \left[ \frac{W^2(1+H^2+H^2)}{(1+H^2)(H^2+W^2)} \right]$$

Figure 9-5. Continued



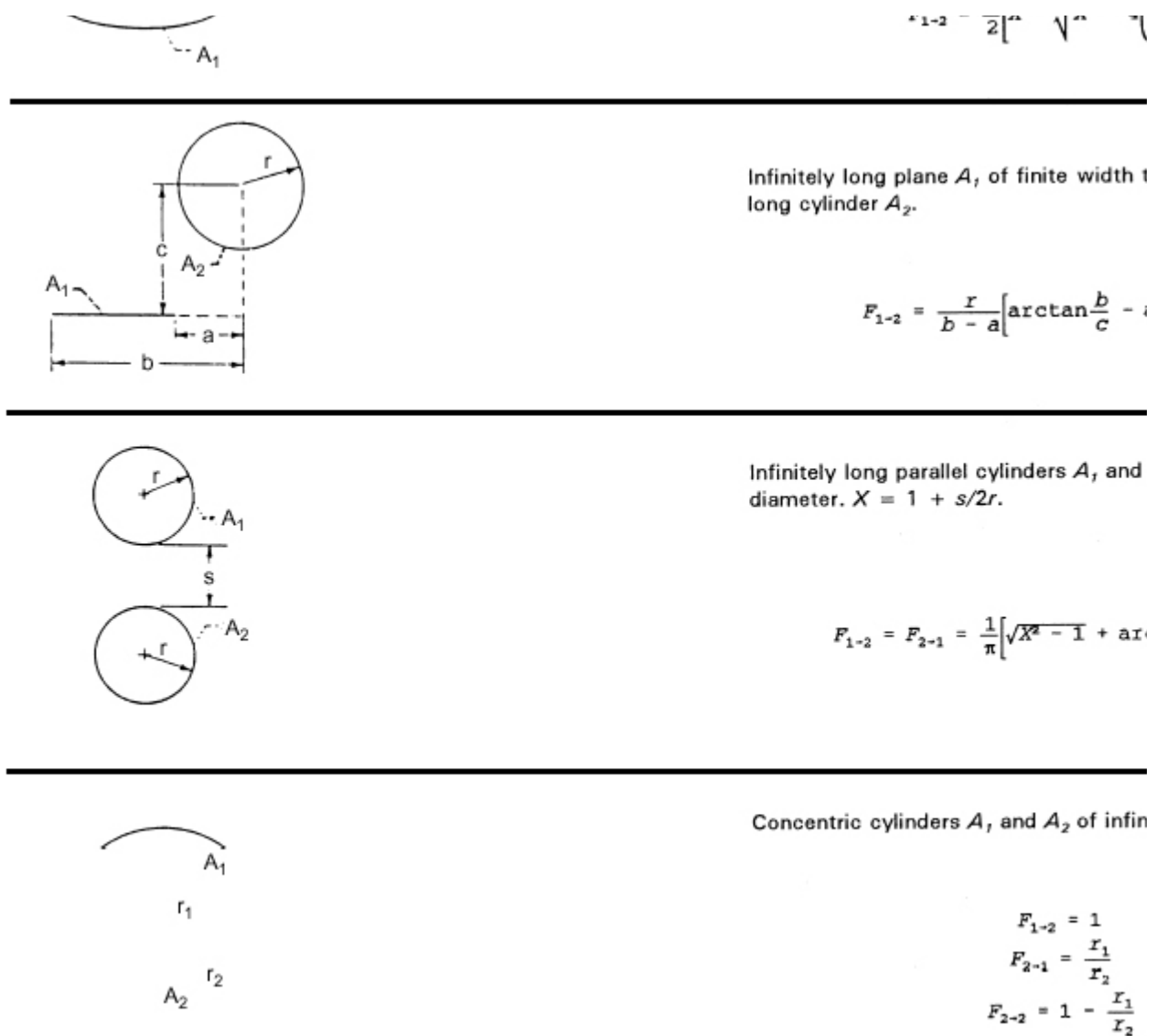
Infinitely long enclosure formed by three surfaces  $A_1$ ,  $A_2$ , and  $A_3$ .

$$F_{1-2} = \frac{A_1 + A_2 - A_3}{2A_1}$$

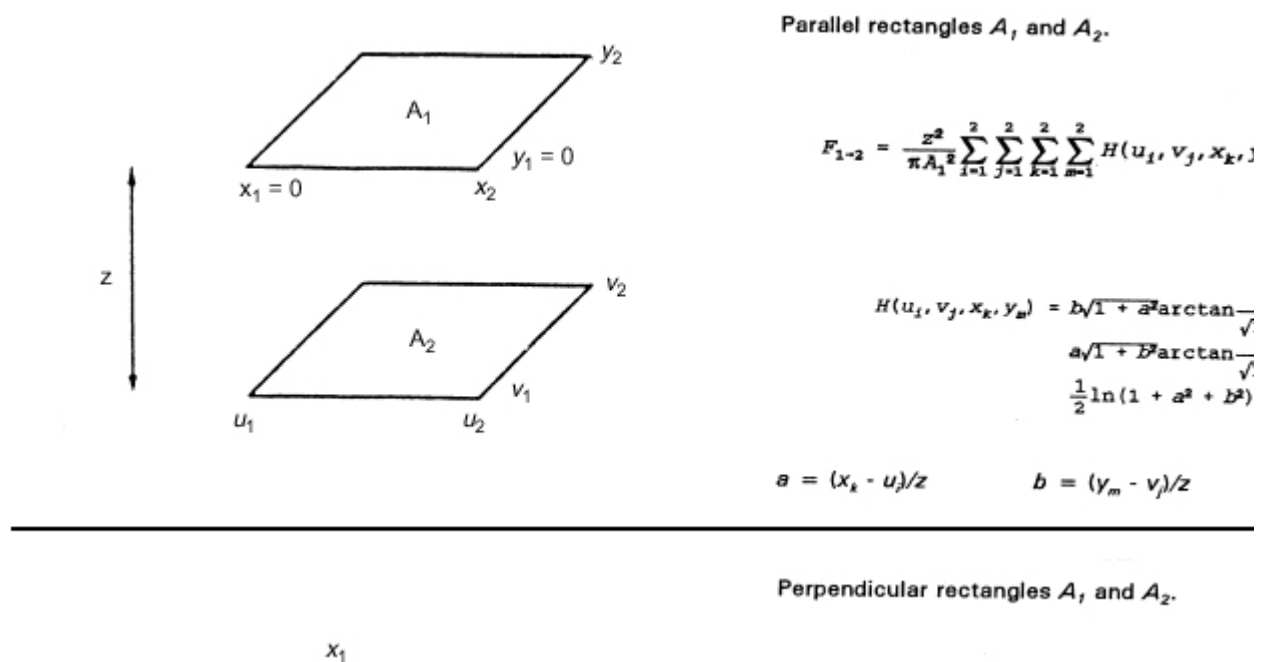


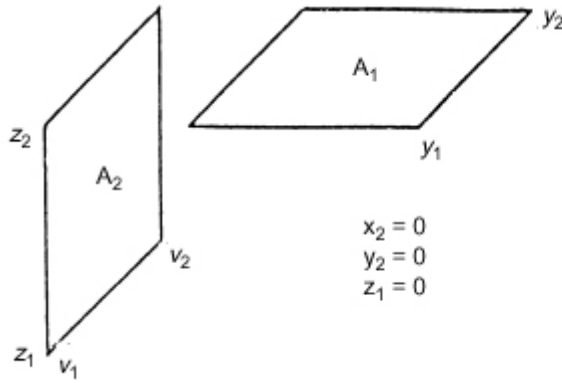
Parallel circular disks  $A_1$  and  $A_2$  with centers  $O_1$  and  $O_2$  on the same normal.  $R_1 = r_1/h$ ;  $R_2 = r_2/h$ ;  $X = \sqrt{R_1^2 + R_2^2}$ .

$$F_{1-2} = \frac{1}{2} \left[ 1 + \sqrt{1 - X^2} \right]$$



**Figure 9-5.** Radiative transfer theory form factors ( $F$ ) for diffuse area sources.





$$F_{1-2} = \frac{1}{2\pi A_1} \sum_{i=1}^2 \sum_{j=1}^2 \sum_{k=1}^2 \sum_{m=1}^2 G(v_i, z_j, x_k, y_m)$$

$$G(v_i, z_j, x_k, y_m) = a\sqrt{c^2 + b^2} \arctan \frac{\sqrt{c^2 + b^2}}{\frac{1}{4}(a^2 - b^2 - c^2)} \ln$$

$$\begin{aligned} a &= y_m - v_i & b &= \bar{z} - z_j \\ \bar{z} &= z\text{-coordinate of surface } A_1 \\ \bar{x} &= x\text{-coordinate of surface } A_2 \end{aligned}$$

**Figure 9-6.** General expressions for form factors ( $F$ ) between parallel and perpendicular rectangles.

$$E_2 = \frac{1}{A_2} \sum_i \sum_j I(\theta_{ij}, \psi_{ij}) \cos \xi_{ij} \frac{a_{1i} a_{2j}}{D_{ij}^2} \quad (9-17)$$

where the summation is over all the discrete pieces of luminaire and the discrete pieces of the receiving surface, and

$I(\theta_{ij}, \psi_{ij})$  = intensity of the  $i$ th piece of the luminaire in the direction of the  $j$ th piece of the receiving surface,

$\xi_{ij}$  = incident angle of flux from the  $i$ th piece of the luminaire,

$a_{1i}$  = area of the  $i$ th piece of luminaire,

$a_{2j}$  = area of the  $j$ th piece of the receiving surface,

$D_{ij}$  = distance between the  $i$ th piece of the luminaire and the  $j$ th piece of the receiving surface,

$A_1$  = area of the luminaire surface,

$A_2$  = area of the receiving surface.

Equation 9-16 can alternatively be evaluated using quasi-Monte Carlo ray casting,<sup>5-7</sup> where the distribution of points that rays are sent from the emitting surface  $A_1$  to the receiving surface  $A_2$  is weighted according to the photometric distribution of the nondiffuse emitting surface.

All of the previous types of analyses are summarized in [Figure 9-7](#). The equation to be used for illuminance calculations is determined by the size of the source, the size of the receiving element, and the nature of the intensity distribution of the source. If the distance between the source and the analysis point is less than five times the largest dimension of the source, the source is considered an area source for the purposes of calculation. This five times rule is discussed in the next section.

| Size of Source | Size of Receiving Element | Distribution | Appropriate Equation |
|----------------|---------------------------|--------------|----------------------|
| Point          | Point                     | Diffuse      | (9-4)                |
|                | Point                     | Nondiffuse   | (9-4)                |
|                | Area                      | Diffuse      | (9-9)*               |
| Area           | Point                     | Diffuse      | (9-9)*               |
|                | Point                     | Nondiffuse   | (9-15)               |
|                | Area                      | Diffuse      | (9-13)*              |



| Area                                                                                                                       | Nondiffuse | (9-17) |
|----------------------------------------------------------------------------------------------------------------------------|------------|--------|
| An asterisk (*) signifies that these equations are available for specific geometries (see Figures 9-2, 9-3, 9-5, and 9-6). |            |        |

**Figure 9-7. Flux Transfer Equations**

## Photometry as the Basis for Calculations

Intensity distributions are used to specify the spatial distribution characteristics of a light source. This description treats the source as a point and gives the luminous intensity. The set is sufficiently large to provide a complete description of the spatial distribution of flux.

The luminous intensity of a light source or luminaire is calculated from measurements of illuminance. Illuminances are obtained at a convenient measurement distance that defines an imaginary sphere with a radius equal to the measurement distance. The sphere center coincides with a fiducial point inside the luminaire. This so-called photometric center is often the origin of the coordinate system used for calculations.<sup>12</sup>

If the source is assumed to be a point, then the intensity and the illuminance are related by Equation 9-4. If the illuminance measurements are made with the surface normal of the illuminance probe oriented to the photometric center, then the cosine of the viewing angle equals 1 and Equation 9-4 becomes

$$E_t = \frac{I}{D_t^2}$$

or

$$I = E_t D_t^2 \quad (9-18)$$

where

$I$  = luminous intensity,  
 $E_t$  = illuminance measurement,  
 $D_t$  = measurement (test) distance.

The luminous intensity is distance invariant, since the product  $E_t D_t^2$  is distance invariant. Thus, the illuminance at any distance is given by Equation 9-4.

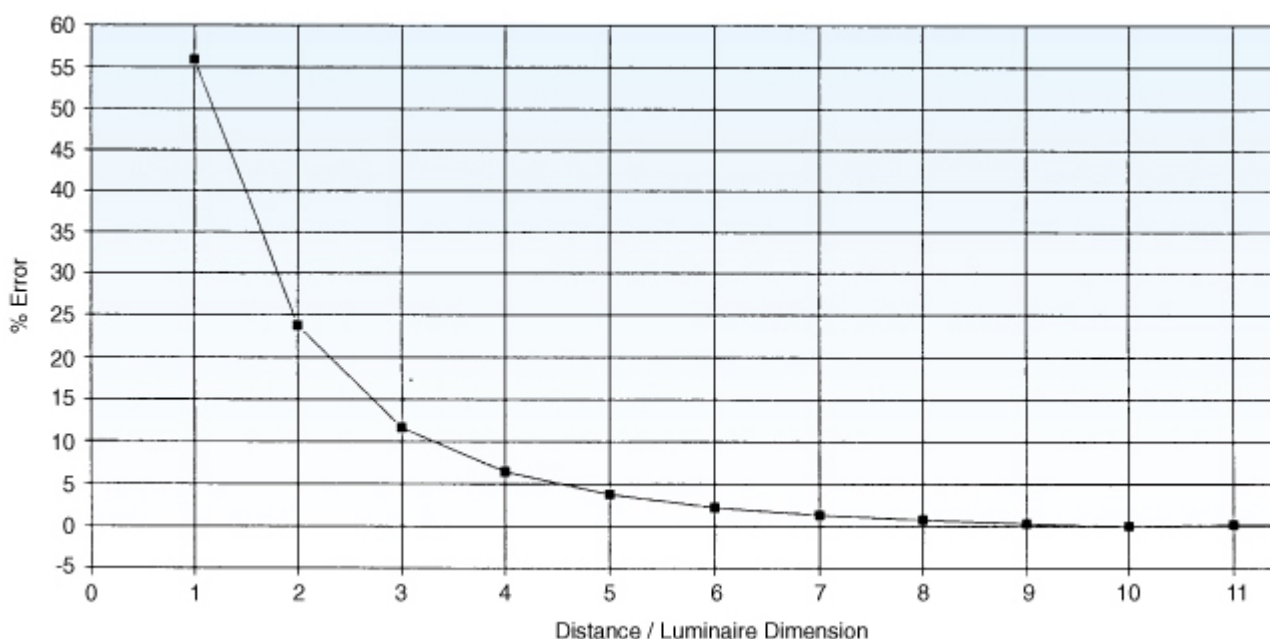
In the photometry of luminaires, Equation 9-18 is generally applied to obtain a relative value of the luminaire's intensity in a particular direction. The magnitude is then determined through photometry of the bare lamps in a procedure known as relative photometry.

## Far-Field Photometry

Assuming the luminaire to be a point source permits the illuminance produced under any geometric circumstance to be calculated. The computational value of intensity distributions rests on the assumption that illuminance varies proportionally to the reciprocal of the distance squared and to the cosine of the incident angle.

Only a point light source produces illuminances that always vary as the inverse squared distance. However, regardless of the luminaire size, it is always possible to choose a distance,  $D_f$  sufficiently large so that illuminances produced at distances greater than  $D_f$  do vary (nearly) as the inverse squared distance. Yamauti<sup>13</sup> and Fock<sup>14</sup> first showed this for diffuse emitters. For these emitters  $D_f$  is five times the maximum dimension of the emitter. This five times rule permits a computational accuracy of at worst 2% for diffuse emitters. In far-field photometry, a distance of at least  $D_f$  is used to make the illuminance measurements from which the luminous intensities are calculated. These intensities can then be used to calculate illuminances at distances greater than  $D_f$  treating the luminaire as a point source. Most commercial photometry uses far-field photometry.

Illuminance calculations that assume the luminaire to be a point source at distances less than  $D_f$  are likely to be inaccurate. As a guide to the inaccuracies that can be expected, Figure 9-8 shows an illuminance error curve for a square diffuse emitter. The error, in percent of the correct value, is given as a function of the ratio of the calculation distance  $D$  to the luminaire dimension. The five times rule requires this ratio to be 5 or larger. Comparison between measurements and predictions using real luminaires gives similar results.<sup>15</sup>



**Figure 9-8.** Demonstration of the five-times rule for photometric measurements.

It should be noted that intensity distributions other than that of a diffuse emitter have different values of  $D_f$ .<sup>16</sup> However, it is customary to apply the five times rule to most indoor luminaire photometry.

## Near-Field Photometry

Near-field photometry describes the spatial flux distribution of a luminaire in a manner permitting accurate illuminance calculations at distances less than  $D_f$ . Near-field photometry is particularly important for analyzing indirect lighting systems. Two types of near-field photometry have been developed expressly for improving computational accuracy.

Application-distance photometry uses test distances that are equal to the distances at which illuminance calculations are made.<sup>17-19</sup> No assumptions about distance invariance are made. In this case the luminaire must be treated as a point source for calculations. Since illuminance calculations are likely to be made at many distances, application-distance photometry provides intensity distributions for several test distances.

Luminance-field photometry<sup>16,20,21</sup> measures and reports the luminance distribution of the luminaire as viewed from a set of points completely surrounding the luminaire. All points are the same distance from the luminaire photometric center. Precisely stated, the data describe a four-dimensional scalar field of luminance. From these luminance data, illuminance can be calculated at any distance and orientation from the luminaire. Luminance-field photometric measurements can be made using a CCD video camera;<sup>22</sup> however, the quantity of data can be difficult to manage.<sup>23</sup>

## Reflection Properties of Surfaces

Useful special cases of reflectance are perfectly diffuse and perfectly specular reflectances. These cases of the spatial distribution permit great simplification of calculations involving the reflection of light from surfaces.

Perfectly diffuse reflection is that for which the luminous intensity in a given direction is proportional to the cosine of the declination angle from the perpendicular to the surface. The flux reflected from a diffuse surface is not a function of the incident direction or the azimuthal angle. Thus, the reflecting surface exhibits a luminance independent of viewing angle.

Perfectly specular reflection is that in which flux is reflected at the mirror angle to the incident direction. That is, the angle of the reflected flux is equal to that of the incident direction with respect to the direction perpendicular to the surface, and the azimuthal separation of the exitant and incident flux is exactly  $180^\circ$ .

Many surfaces and finishes used in architecture exhibit a reflectance that is sufficiently diffuse to be considered perfectly diffuse. This is important for computational purposes, since they can be considered diffuse emitters regardless of the incident direction of the light.

In some cases, assumptions about diffuseness lead to very inaccurate results. An example of this is the calculation of the luminance of visual tasks, such as pencil marks on paper, etched marks on a rule, and roadway surfaces. The bidirectional reflectance distribution function (BRDF) of a surface must be used in these cases.<sup>24</sup>

In addition to simplifying the spatial distribution characteristics of reflectance, it is often permissible (and necessary) to simplify its spectral characteristics. All surfaces exhibit a reflectance that varies with the wavelength of the incident light. The reflectance reported for a particular surface is usually obtained by integrating the proportion of light reflected from the surface at all visible wavelengths. Although the reflectance so defined changes if the spectrum of the illuminant changes, it is a useful approximation to assume that the reflectance is spectrally flat. The surface is assigned a "gray reflectance" equal to the integrated value. Thus, it is assumed that the surface exhibits the same reflectance regardless of the spectral power distribution of incident light used in calculations. This is referred to as the "gray assumption."

Although this simplifies calculations and usually introduces only small errors, difficulties can arise. The reflectance of a surface with a deeply saturated color usually has a significant spectral

reflectance only in a narrow band of wavelengths. Use of a light source spectrally different from that used in making a reflectance standard can then lead to large errors.

## Interreflection of Light

Some of the light incident on an architectural surface is absorbed, and some is reflected. The reflected portion radiates to other surfaces, where it is absorbed and reflected again. This can be thought of as happening an infinite number of times. The phenomena of repeated exchange of light by multiple reflection is called interreflection.<sup>25-28</sup> Architectural surfaces are made luminous by interreflection, as well as by light that reaches them directly from sources such as luminaires and windows. The exitances that these surfaces exhibit under these circumstances are said to be those at luminous equilibrium. That is, they are the exitances present when the rate at which light is being provided by luminaires and daylighting is balanced by the rate at which it is being absorbed by surfaces. These exitances are called final exitances, in contrast with initial exitances, which are those produced directly by light from luminaires or daylighting, before the process of interreflection.

Surfaces made luminous by interreflections become additional sources of light that should be considered when determining illuminance. The illuminance produced by reflected light is termed the interreflected component. In most architectural settings it is usually assumed that the surfaces involved exhibit a diffuse reflectance and therefore are diffuse emitters. They can then be treated as diffuse area sources, and the illuminance is calculated using the equations for a diffuse area source, involving configuration factors and surface exitance. The total interreflected component at an analysis point is

$$E_{\text{inter}} = \sum_{i=1}^n c_{i \rightarrow p} M_i \quad (9-19)$$

where

$c_{i \rightarrow p}$  = configuration factor from surface  $i$  to point  $p$ ,

$M_i$  = diffuse exitance of surface  $i$ .

Thus, calculating the interreflected component of illuminance requires the determination of the final exitance of surfaces that are luminous by interreflection.

The most useful calculation procedure for determining the final exitances is the finite-element method.<sup>29-31</sup> The surfaces in the space are discretized, and each element is assumed to have a different but uniform exitance. In most cases it also can be assumed that the reflectances are perfectly diffuse. The accuracy of the calculated luminance pattern depends on the size of the zones and on the degree to which the reflectances are diffuse.

Modeling room surfaces as discrete elements not only allows an approximation to the actual exitance pattern in the room, but such modeling can also represent the effect of doors, windows, bulletin boards, and chalkboards.<sup>29</sup> Since these surfaces generally differ from the walls in reflectance, their exitance is also different, as is their effect on the illuminance within the space.

The degree to which the pattern of exitance in the enclosure is represented by the assemblage of discrete zone exitances depends on the zone size. A highly variable directional component, such as one that can be produced by an indirect lighting or wall-washing system, may require a small

discretization of surfaces. This permits an accurate model of the large luminance gradient.

In advanced models, interior obstructions such as partitions, shelves, and furniture can also be considered.<sup>32,33</sup> Other methods have been developed to reduce the amount of work required to solve such systems,<sup>34-36</sup> and approximations for calculations in spaces with interior obstructions have also been developed.<sup>37</sup>

Numerous techniques based on radiative flux transfer theory<sup>5,6</sup> (also known as radiosity methods) and ray tracing<sup>38</sup> have been developed by the computer graphics community. While these techniques have been developed primarily for architectural rendering, they are based on physical principles<sup>5,23</sup> and so can be applied to illumination engineering problems as well.

Radiosity methods model perfectly diffuse reflections, whereas ray tracing techniques are best suited to modeling specular reflections. However, hybrid techniques have been developed to accurately model both diffuse and specular reflections.<sup>23,39,40</sup>

## The Radiative Transfer Equation<sup>5-7,10,11,22,23,38-43</sup>

To obtain the equations for calculating interreflection, a flux balance equation is written for each element. It equates the total flux leaving an element to the total incident flux multiplied by the element's reflectance. The total incident flux has both a direct component due to electric and daylight sources and an interreflected component due to the flux from all the other elements. The equality expressing the flux balance exists when all interreflections are taken into account. For the  $i$ th element of a radiative transfer system, the equation is

$$M_i = M_{0i} + \rho_i(f_{i \rightarrow 1}M_1 + f_{i \rightarrow 2}M_2 + \dots + f_{i \rightarrow m-1}M_{m-1} + f_{i \rightarrow m}M_m) \quad (9-20)$$

This can be written for each surface element in the system, and a set of linear, independent, simultaneous equations results. Expressed in matrix form, this gives

$$\begin{bmatrix} M_1 \\ M_2 \\ \vdots \\ M_m \end{bmatrix} = \begin{bmatrix} M_{01} \\ M_{02} \\ \vdots \\ M_{0m} \end{bmatrix} + \begin{bmatrix} \rho_1 f_{1 \rightarrow 1} & \rho_1 f_{1 \rightarrow 2} & \dots & \rho_1 f_{1 \rightarrow m-1} & \rho_1 f_{1 \rightarrow m} \\ \rho_2 f_{2 \rightarrow 1} & \rho_2 f_{2 \rightarrow 2} & \dots & \rho_2 f_{2 \rightarrow m-1} & \rho_2 f_{2 \rightarrow m} \\ \vdots & \vdots & & \vdots & \vdots \\ \rho_m f_{m \rightarrow 1} & \rho_m f_{m \rightarrow 2} & \dots & \rho_m f_{m \rightarrow m-1} & \rho_m f_{m \rightarrow m} \end{bmatrix} \times \begin{bmatrix} M_1 \\ M_2 \\ \vdots \\ M_m \end{bmatrix} \quad (9-21)$$

where

$m$  = number of zones in the system,

$M_i$  = exitance of the  $i$ th zone, due to direct and interreflected flux (the equation is solved for these values),

$\rho_i$  = diffuse reflectance of the  $i$ th zone,

$M_{0i}$  = exitance due to the direct component on the  $i$ th zone (due to luminaires and daylight sources),

$f_{i \rightarrow j}$  = form factor from zone  $i$  to zone  $j$  (note that for planar zones,  $f_{i \rightarrow i} = 0$ ).

For simple geometries, the form factors can be computed using the equations found for parallel and orthogonal rectangles in [Figures 9-5](#) and 9-6. For complex geometries, and especially for environments with occluding objects, it is necessary to use numerical integration methods such as hemicubes and Monte Carlo ray casting.

The above matrix equation can be rewritten in terms of the illuminance on each surface. This form is particularly valuable when one or more of the reflectances is assigned a value of zero, since then the illuminance striking each element is independent of the element's reflectance:

$$\begin{bmatrix} E_1 \\ E_2 \\ \vdots \\ E_m \end{bmatrix} = \begin{bmatrix} E_{01} \\ E_{02} \\ \vdots \\ E_{0m} \end{bmatrix} + \begin{bmatrix} \rho_1 f_{1 \rightarrow 1} & \rho_1 f_{1 \rightarrow 2} & \cdots & \rho_1 f_{1 \rightarrow m-1} & \rho_1 f_{1 \rightarrow m} \\ \rho_2 f_{2 \rightarrow 1} & \rho_2 f_{2 \rightarrow 2} & \cdots & \rho_2 f_{2 \rightarrow m-1} & \rho_2 f_{2 \rightarrow m} \\ \vdots & \vdots & & \vdots & \vdots \\ \rho_m f_{m \rightarrow 1} & \rho_m f_{m \rightarrow 2} & \cdots & \rho_m f_{m \rightarrow m-1} & \rho_m f_{m \rightarrow m} \end{bmatrix} \times \begin{bmatrix} E_1 \\ E_2 \\ \vdots \\ E_m \end{bmatrix} \quad (9-22)$$

The simplest way to solve these large matrix finite-element systems is to use the method of iteration.<sup>5,40</sup> The iteration begins by setting the vector  $M$  equal to the exitance vector  $M_0$  in Equation 9-21, using this as an initial estimate of the system. This initial estimate is then used on the right-hand side of the equation to generate another estimate of the solution vector on the left.

Various iteration methods may be employed. Jacobi iteration exactly simulates physical reflections and absorption of light within an environment.<sup>23</sup> Faster convergence is usually obtained with Gauss-Seidel iteration,<sup>43</sup> typically within five to ten iterations for simple environments with relatively few elements.

Gauss-Seidel iteration has the disadvantage that the entire form factor matrix is required for each iteration. This limits the number of elements that can be modeled using computer simulations. A variation of Southwell iteration called progressive refinement<sup>6</sup> is preferred in that only one column of the form factor matrix is required for each iteration. This permits the modeling of complex environments with hundreds of thousands of elements, with convergence attained in a few minutes using desktop computers.<sup>40</sup>

It should be noted that maintained values of the exitance might differ from initial values. Should computation of maintained values be required, the surface reflectances used in the computation of the reflected component should be the reflectances expected under maintained conditions in the environment. Additionally, a light loss factor should be used in the calculation of the initial exitances.

## Implementation of the Flux Balance Model

The simplest example of a radiative transfer problem solved by this method is a system with two surfaces. In this case, two equations in two unknowns result. The solution is

$$M_1 = \frac{M_{01} + M_{02} \rho_1 f_{1 \rightarrow 2}}{1 - \rho_1 \rho_2 f_{1 \rightarrow 2} f_{2 \rightarrow 1}} \quad (9-23a)$$

$$M_2 = \frac{M_{02} + M_{01} \rho_2 f_{2 \rightarrow 1}}{1 - \rho_1 \rho_2 f_{1 \rightarrow 2} f_{2 \rightarrow 1}} \quad (9-23b)$$

where

$M_1$  = final exitance of surface 1, taking account of interreflection,

$M_2$  = final exitance of surface 2, taking account of interreflection,

$M_{01}$  = initial exitance of surface 1,

$M_{02}$  = initial exitance of surface 2,

$\rho_1$  = diffuse reflectance of surface 1,

$\rho_2$  = diffuse reflectance of surface 2,

$f_{2 \rightarrow 1}$  = form factor from surface 2 to surface 1,

$f_{1 \rightarrow 2}$  = form factor from surface 1 to surface 2.

These equations provide a way to estimate the effects of interreflection in situations involving only two surfaces, or where only two elements of a large system participate in interreflection.

Another example of how a simple flux balance model can be applied to the analysis of a lighting system is the three-surface model used in the lumen method (Figure 9-9).<sup>44-46</sup> The geometric arrangement is an empty rectangular room with recessed lighting equipment. The lighting system provides a general uniform illuminance on the workplane. Perfectly diffuse reflectances on all surfaces are assumed, and the same reflectance is assumed for the four wall surfaces. This allows the four walls to be treated as one surface. The average illuminance on the floor is to be calculated.

For the purposes of the finite-element procedure, then, there are three elements or zones in this room: ceiling, walls, and floor. The surfaces have initial exitances  $M_{0c}$ ,  $M_{0w}$ , and  $M_{0f}$  respectively. These initial exitances are due to the flux falling on the surfaces from the luminaires within the room.

Since there are interreflections, the final exitances  $M_c$ ,  $M_w$ , and  $M_f$  can be expressed as follows:



$$M_c = M_{0c} + \rho_c (M_w f_{c \rightarrow w} + M_f f_{c \rightarrow f}) \quad (9-24)$$

$$M_w = M_{0w} + \rho_w (M_c f_{w \rightarrow c} + M_w f_{w \rightarrow w} + M_f f_{w \rightarrow f}) \quad (9-25)$$

$$M_f = M_{0f} + \rho_f (M_c f_{f \rightarrow c} + M_w f_{f \rightarrow w}) \quad (9-26)$$

where

$M_c$  = final ceiling exitance,

$M_w$  = final wall exitance,

$M_f$  = final floor exitance,

$M_{0c}$  = initial ceiling exitance,

$M_{0w}$  = initial wall exitance,

$M_{0f}$  = initial floor exitance,

$\rho_f$  = floor reflectance,

$\rho_w$  = wall reflectance,

$\rho_c$  = ceiling reflectance,

$f_{f \rightarrow c}$  = form factor from floor to ceiling,

$f_{f \rightarrow w}$  = form factor from floor to walls,

$f_{w \rightarrow c}$  = form factor from walls to ceiling,

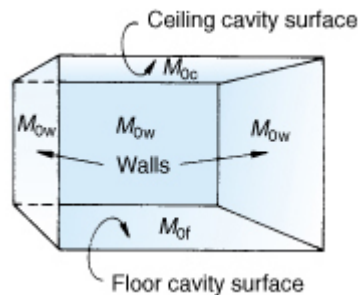
$f_{w \rightarrow w}$  = form factor from walls to walls,

$f_{w \rightarrow f}$  = form factor from walls to floor,

$f_{c \rightarrow w}$  = form factor from ceiling to walls,

$f_{c \rightarrow f}$  = form factor from ceiling to floor.

With these three equations and the form factors, any interior illuminance or exitance can be determined. The above set of simultaneous equations is the basis for generating the tables of the coefficients of utilization, the wall exitance coefficients, and the ceiling cavity exitance coefficients.



**Figure 9-9.** Radiative transfer theory diagram.

This simple geometry permits the remaining six form factors to be determined from the form factor,  $f_{c \rightarrow f}$  between floor and ceiling, using reciprocity and the flux balance requirement (the sum of all form factors leaving a single surface must sum to 1.0 for a closed system).



$$f_{f \rightarrow c} = f_{c \rightarrow f} \quad (9-27)$$

$$f_{c \rightarrow w} = f_{f \rightarrow w} = 1 - f_{c \rightarrow f} \quad (9-28)$$

$$f_{w \rightarrow c} = f_{w \rightarrow f} = \frac{A_c}{A_w} (1 - f_{c \rightarrow f}) \quad (9-29)$$

$$f_{w \rightarrow w} = 1 - 2f_{w \rightarrow c} \quad (9-30)$$

In these equations,  $A_c$  and  $A_w$  are the surface areas of the ceiling and walls, respectively. This three-surface model is the simplest of all flux transfer models for interior lighting calculations. It assumes that flux strikes each surface in a uniform manner and does not include variations in illuminance across any surface. In accordance with the Commission Internationale de l'Éclairage (CIE) practice and for the lumen method described below, the standard lighting coefficient tables are based upon a length-to-width ratio of 1.6 and given as a function of the room cavity ratio (RCR) only. [Figure 9-10](#) gives numerical values for the various form factors.

The lumen method extends the utility of this three-surface model by letting the ceiling and floor surfaces be virtual surfaces that are actually openings into rectangular cavities. These virtual surfaces are assigned effective reflectances. The top virtual surface is a plane containing the luminaires, and the cavity that this virtual surface represents extends from the luminaires up to the ceiling. The bottom virtual surface is the workplane, and the cavity that this virtual surface represents extends from the workplane down to the floor. Note that the average illuminance onto the workplane is its final exitance divided by its effective reflectance.

| RCR | $F_{w \rightarrow w}$ | $\frac{F_{w \rightarrow c}}{F_{w \rightarrow f}}$ | $\frac{F_{c \rightarrow w}}{F_{f \rightarrow w}}$ | $\frac{F_{c \rightarrow f}}{F_{f \rightarrow c}}$ |
|-----|-----------------------|---------------------------------------------------|---------------------------------------------------|---------------------------------------------------|
| 0   | 0.000                 | 0.500                                             | 0.000                                             | 1.000                                             |
| 1   | .133                  | .434                                              | .173                                              | .827                                              |
| 2   | .224                  | .388                                              | .311                                              | .689                                              |
| 3   | .298                  | .351                                              | .421                                              | .579                                              |
| 4   | .361                  | .320                                              | .511                                              | .489                                              |
| 5   | .415                  | .292                                              | .585                                              | .415                                              |
| 6   | .463                  | .269                                              | .645                                              | .355                                              |
| 7   | .504                  | .248                                              | .694                                              | .306                                              |
| 8   | .540                  | .230                                              | .735                                              | .265                                              |
| 9   | .573                  | .214                                              | .769                                              | .231                                              |
| 10  | .601                  | .199                                              | .798                                              | .202                                              |

The length:width ratio is 1.6:1.

**Figure 9-10.** Form Factors for a Zonal-Cavity System

Although more complicated, exactly the same procedure can be used for models of radiative transfer in a room that uses more than three surfaces (the finite-element method). Complex models can have thousands of discrete elements as each surface in the room is divided into a collection of smaller zones.<sup>34-36</sup> The result is a more detailed knowledge of the room surface exitance distributions.

## Monte Carlo Ray Tracing<sup>7</sup>

One disadvantage of the simple flux balance models is that they can model reflections only from perfectly diffuse surfaces. Although this is adequate for most lighting calculations and architectural renderings, it does not provide sufficient information for estimating veiling reflections from specular surfaces and glare calculations.

Ray tracing techniques provide a more realistic model for the behavior of light, including reflection from specular surfaces and refraction by transparent objects. Reflections from diffuse surfaces can be approximated by reflecting hundreds of rays in random directions from each incident ray.<sup>6</sup> By providing appropriate weights to different directions of ray incidence and reflection, arbitrary bidirectional reflectance distribution functions can also be modeled.

Ray tracing is mathematically equivalent to radiative flux transfer between point emitters and receivers. Whereas evaluation of Equation 9-22 provides estimates for the illuminance of each surface element, Monte Carlo ray tracing provides similar estimates for random points on each surface. Illuminances for surface elements can then be obtained through Monte Carlo integration.

Rays can be traced either from the light sources into the environment (photosimulation)<sup>6,39</sup> or from the observer into the environment (path tracing).<sup>23,38,39</sup> Photosimulation methods are useful in that they provide accurate exitances for all surface elements in the environment. Path tracing methods are useful in that they provide accurate luminances for all surfaces within the observer's field of view, including veiling and specular reflections.

The disadvantage of ray tracing techniques is that millions to hundreds of millions of rays must be evaluated in order to reduce the variance of the solutions to acceptable levels. While various statistical techniques can be used to ensure that randomly chosen ray directions transport on average the maximum amount of flux between surfaces,<sup>6</sup> convergence of the radiative transfer equation using ray tracing techniques is typically slow in comparison to finite element methods.

## Lighting Simulation Programs

The radiative transfer equation can be solved using finite element (radiosity) methods, ray tracing techniques, and hybrid approaches. These approaches are collectively referred to as global illumination algorithms by the computer graphics community.<sup>23</sup> Unlike simpler computer graphics techniques, global illumination algorithms are based on physical principles. Because they model the physical behavior of light, they can be used in lighting simulation software programs to create photorealistic architectural renderings and perform sophisticated illumination engineering calculations.

## APPLICATION ISSUES

### Characterizing Light for Calculation Purposes

Lighting calculations are generally divided into two components for the purpose of determining the amount of light reaching a point in space. The direct component comprises light reaching the point directly from the luminaires or windows. The interreflected component is comprised of light reaching the same point from surfaces due to interreflections.

**Direct Component.** The direct component must be determined for points of interest on the workplane and for any reflecting surfaces considered in the analysis. The contribution to the reflecting surfaces is used to provide the starting condition for interreflections. On the workplane,

the direct component may have special importance because it is the principal component responsible for veiling reflections. Under a typical direct lighting system, the direct component provides the majority of the total illuminance on the workplane. In outdoor lighting situations, the direct component may be the only light that a point receives. The direct component can be determined using the inverse square law or one of the area source methods if the luminaires are large compared to the distances involved. Methods have been developed that take advantage of either special geometries or intensity distributions.<sup>47-51</sup>

**Interreflected Component.** In most lighting calculations, the interreflected component requires the most time-consuming calculation. The amount of work involved in solving the large matrix problem is proportional to the square of the number of elements involved. To determine the interreflected component, the initial illuminance or direct component must first be determined at each of the discrete elements. In most cases, the value at the center of each element is used as an approximation of the average illuminance across an element. If the elements are sufficiently small, the error involved in this assumption is minimal. Large elements require more careful determinations of the average initial exitance, such as integration methods or calculation of several points to get an average.

Determination of the interreflected component is critical in situations where it is likely to be large relative to the direct component. Situations where this may be true include coves, valences, and indirect lighting applications. It is important that the discretization scheme and calculation model being used for the direct component be capable of providing a light distribution that accurately models that provided by the lighting system.<sup>3,32</sup> Near-field photometry may be required for such calculations.<sup>22,42</sup>

In some cases, a much less rigorous interreflection model may be applied. If the direct component is certain to dominate at the analysis points of interest, it may be possible to use a rather simple interreflected component calculation method involving larger and fewer room surface elements. When using large elements, it is important to remember that the value at the center of a large surface does not necessarily approximate the average across it. The total luminous flux striking the surface should be determined and then divided by the area to determine the average illuminance on the surface.

In the simplest approximation, the room is approximated with three surfaces, as used in the lumen method described below, and the interreflected component is calculated using the three surface exitances that result from the lumen method approximation.

## **Light Loss Factors<sup>52-55</sup>**

Light loss factors adjust lighting calculations from a controlled laboratory environment to actual field conditions. They represent differences in lamp lumen output, luminaire output, and surface reflectances between the two sets of conditions. Calculations based on laboratory data alone are likely to provide unrealistically high values if not modified by light loss factors.

Light loss factors are divided into two groups: recoverable and nonrecoverable ([Figure 9-11](#)). Recoverable factors are those that can be changed by regular maintenance, such as cleaning and relamping luminaires and cleaning or painting room surfaces. Nonrecoverable factors are those attributed to equipment and site conditions and cannot be changed with normal maintenance.

Light loss factors are assumed to represent independent effects and are therefore multiplicative. The total light loss factor (LLF) is the product of all the applicable factors listed in [Figure 9-11](#). No factor should be ignored (set equal to 1) until investigations justify doing so. Lighting

calculations should not be attempted until all light loss factors are considered.

---

|                                       |
|---------------------------------------|
| Nonrecoverable                        |
| Luminaire ambient temperature factor  |
| Heat extraction thermal factor        |
| Voltage-to-luminaire factor           |
| Ballast factor                        |
| Ballast-lamp photometric factor       |
| Equipment operating factor            |
| Lamp position (tilt) factor           |
| Luminaire surface depreciation factor |
| Recoverable                           |
| Lamp lumen depreciation factor        |
| Luminaire dirt depreciation factor    |
| Room surface dirt depreciation factor |
| Lamp burnout factor                   |

---

**Figure 9-11. Light Loss Factors**

**Nonrecoverable Factors.** The nonrecoverable factors usually are not controlled by lighting maintenance procedures. Some exist initially and continue through the life of the installation, either being of such little effect as to make correction needless, or being too costly to correct. However, all should be studied because they can diminish the planned luminous output of the lighting system.

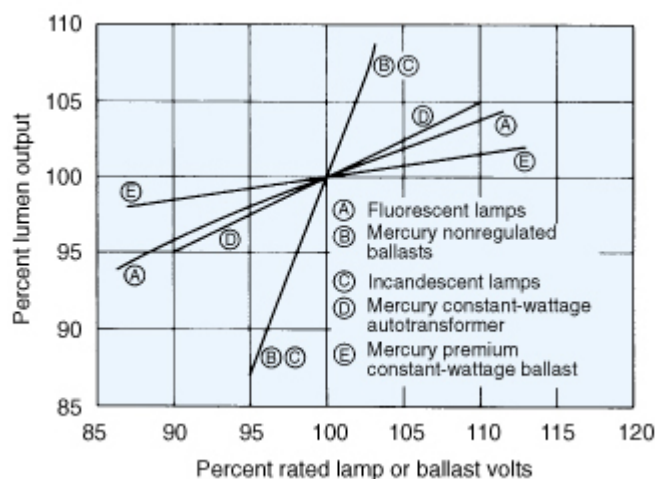
*Luminaire Ambient Temperature Factor.* The effect of ambient temperature on the output of some fluorescent lamp luminaires is considerable. Variations in temperature, within the range of those normally encountered in interiors, have little effect on the light output of incandescent and high-intensity discharge lamp luminaires but appreciably affect the light output of fluorescent luminaires. The luminaire ambient temperature factor is the fractional lumen loss of a fluorescent luminaire due to internal luminaire temperatures differing from the temperatures at which photometry was performed. This factor should take into consideration any variation in the temperature around the luminaire, the means and conditions of mounting the luminaire, and the use of any insulation in conjunction with the application of the luminaire.

Generally, firm data on this factor are not available but can be estimated on the following basis. Luminaire photometry is performed in 25° C (77° F) ambient still air. For each degree of rise in ambient temperature above this value, the cold-spot temperature on a fluorescent lamp rises by about 0.6° C (1° F). The effect of lamp temperature rise can be estimated from the manufacturer's literature, recognizing that lamps in luminaires generally operate at temperatures greater than the optimum. Judgment must be applied to factors such as the effect of open versus enclosed luminaires, possible air movement, and the fact that the plenum temperature has a greater effect than the room temperature on recessed luminaires.

*Heat Extraction Thermal Factor.* Air-handling fluorescent luminaires are integrated with the HVAC system as a means of introducing or removing air. This has an effect on lamp temperature and consequently on lamp lumens. The heat extraction thermal factor is the fractional lumen loss or gain due to the air flow. Generally, manufacturers provide specific luminaire test data for this factor at various air flows. Typically, the factor approaches a constant value for air flows in excess of 10 to 20 ft<sup>3</sup>/min through the lamp compartment of a luminaire.

*Voltage-To-Luminaire Factor.* In-service voltage is difficult to predict, but high or low voltage at the luminaire affects the luminous output of most luminaires. For incandescent units, a 1% voltage deviation causes approximately a 3% change in lumen output. For mercury lamp

luminaires with high-reactance ballasts there is a change in lumen output of approximately 3% for each 1% change in primary voltage deviation from rated ballast voltage. When regulated-output ballasts are used, the lamp lumen output is relatively independent of primary voltage within the design range. The luminous output of fluorescent luminaires using conventional magnetic ballasts changes approximately 1% for each 2.5% change in primary voltage. [Figure 9-12](#) shows these variations in graphic form. Different characteristics apply to electronic or energy-saving magnetic ballasts and depend on specific design parameters (see [Chapter 6](#), Light Sources).



**Figure 9-12.** Light output change due to voltage change.

**Ballast Factor.** The lumen output of fluorescent lamps depends on the ballast used to drive the lamps. The lumen output from lamps on commercial ballasts generally differs from that of lamps on the standard reference ballast used for determining rated lumens. For this reason, a multiplicative ballast factor is required to correct nominal rated lamp lumens to actual luminaire performance. The ballast factor is the fractional flux of a fluorescent lamp or lamps operated on the actual ballast divided by the flux when operated on the standard (reference) ballast specified for rating lamp lumens. Ballast factors are determined in accordance with the American National Standard Methods of Measurement of Fluorescent Lamp Ballasts.<sup>56</sup> Manufacturers should be consulted for necessary factors. Data on ballast factors for electronic ballasts are available.<sup>57</sup> Some representative values are shown in [Chapter 6](#), Light Sources. Note that when uncertified ballasts are used, there may be no reliable data available.

The ballast factor depends on the lamp as well as on the ballast, so that a ballast factor developed for a standard lamp does not apply when, for example, an energy-conserving lamp is used, even though the ballast is the same. Magnetic ballasts bearing the label of Certified Ballast Manufacturers (CBM) have a ballast factor that is not less than 0.925 for standard 30- and 40-W rapid start lamps; the ballast factor for such ballasts is frequently estimated at between 0.94 and 0.95. The ballast factor for highly loaded rapid start lamps is 0.95, and for various low-wattage lamps is 0.90.

However, the American National Standards Institute (ANSI)<sup>56</sup> test method for the ballast factor specifies that the test be performed on a cold ballast (for convenience in testing). Significant temperature rise occurs for operating ballasts in luminaires. This causes additional lumen loss, usually on the order of 1.5%, but values as high as 2.5 to 3.5% have been reported. Consequently, a conservative estimate of the operational ballast for a CBM certified ballast would be 0.93.

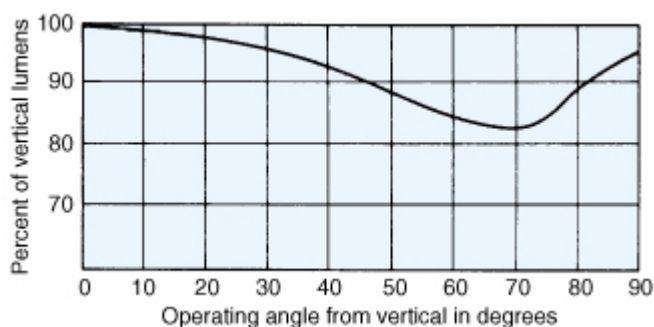
**Ballast-Lamp Photometric Factor.** Fluorescent lamp luminaire photometry is performed at a standard ambient temperature of 25° C (77° F). The lamp temperature differs from this value

when rated lamp lumens are determined. The consequent lamp lumen change from rated lumens is incorporated into the photometric data. The lamp temperature within the luminaire depends on the particular combination of ballast (standard magnetic, energy-efficient magnetic, or electronic) and lamps (standard loading, reduced-power, and energy-efficient). For this reason the photometric data apply only to the specific lamp and ballast types used in the tests. This also applies to the derived data such as coefficients of utilization and exitance coefficients.

Lamp lumen variations cause a change in the magnitude but not in the spatial distribution of fluorescent luminaire intensity. Consequently, all photometric data can be corrected by a multiplicative factor for ballast and lamp types that differ from those used in the photometric tests. This factor is the ballast-lamp photometric factor, and it is measured for a specific ballast-lamp combination in relation to those used in the luminaire photometry. Values for it are available as part of the luminaire photometric report or from the manufacturer. Note that this factor includes adjustment for lamp and ballast changes at the photometric test temperature of 25° C (77° F). The luminaire ambient temperature factor is a separate correction for differences between the laboratory and the expected luminaire installation temperature.

*Equipment Operating Factor.* The lumen output of high-intensity discharge (HID) lamps depends on the ballast, the lamp operating position, and the effect of power reflected from the luminaire back onto the lamp. These effects are collectively incorporated in the equipment operating factor (EOF), which is defined as the ratio of the flux of an HID lamp-ballast-luminaire combination, in a given operating position, to the flux of the lamp-luminaire combination operating in the position for rating the lamp lumens and using the standard (reference) ballasting specified for rating lamp lumens. Equipment operating factors are determined in accordance with the IES Approved Method for Determining Luminaire-Lamp-Ballast Combination Operating Factors for High-Intensity Discharge Luminaires.<sup>58</sup>

*Lamp Position or Tilt Factor (Part of EOF).* For HID lamps, the lamp position factor (sometimes known as the tilt factor) is the ratio of the flux of a HID lamp in a given operating position to the flux when the lamp is operated in the position at which the lamp lumens are rated. This factor is determined at constant lamp wattage and constitutes part of the equipment-operating factor. The lamp position factor is reasonably consistent for mercury lamp types. However, for metal halide lamps it is variable from lamp to lamp and depends on the operating history; thus, it is not actually a constant even for a given lamp.<sup>59,60</sup> Figure 9-13 presents typical average data for the lamp position factor; manufacturers should be consulted regarding specific lamp types.



**Figure 9-13.** Lumen output for HID lamps as a function of operating position.

*Luminaire Surface Depreciation Factor.* Luminaire surface depreciation results from adverse changes in metal, paint, and plastic components that result in reduced light output. Surfaces of glass, porcelain, or processed aluminum have negligible depreciation and can be restored to original reflectance. Baked enamel and other painted surfaces have a permanent depreciation because all paints are porous to some degree. Among plastics, acrylic is least susceptible to



change, but its transmittance may be reduced by use over a period of 15 to 20 years in certain atmospheres. For the same usage, polystyrene has lower transmittance than acrylic and depreciates faster.

Because of the complex relationship between the light-controlling elements of luminaires using more than one type of material (such as a lensed troffer), it is difficult to predict losses due to deterioration of materials. Also, for luminaires with one type of surface, the type of atmosphere in the installation affects the losses. No factors for this effect are available at present.

**Recoverable Factors.** Recoverable factors always need to be considered in determining the total light loss factor. The magnitude of each depends on the maintenance procedures to be used in addition to the physical environment and the lamps and luminaires to be installed.

*Lamp Lumen Depreciation Factor.* The lumen outputs of lamps change gradually and continuously over their operating lives, even with constant operating conditions. In almost all cases, the lumens decrease. The lamp lumen depreciation (LLD) factor is the fraction of the initial lumens produced at a specific time during the life of the lamp. Information about LLD as a function of the hours of lamp operation is available from manufacturers' tables and graphs for lumen depreciation and mortality of the chosen lamp. The rated average life should be determined for the expected number of hours per start; it should be known when burnouts begin in the lamp life cycle. From these facts, a practical group relamping cycle can be established, and then, based on the hours elapsed to lamp removal, the LLD factor can be determined. Consult [Chapter 6](#), Light Sources, or manufacturers' data for LLD factors. 70% of average rated life is the recommended criterion for lamp replacement for both group and spot relamping programs. It should be noted that some electronic ballasting systems compensate to varying degrees for change in lamp lumen output through life, either by an average correction or by feedback control.

*Luminaire Dirt Depreciation Factor.* The accumulation of dirt on luminaires results in a loss in light output, and therefore a loss on the workplane. This loss is known as the luminaire dirt depreciation (LDD) factor and is determined as follows:

1. The luminaire maintenance category is selected from manufacturers' data or by using [Figure 9-14](#).
2. The atmosphere (one of five degrees of dirt conditions) in which the luminaire operates is found as follows. Dirt in the atmosphere comes from two sources: that passed from adjacent air, and that generated by work done in the vicinity. Dirt may be classified as adhesive, attracted, or inert, and it may come from intermittent or constant sources. Adhesive dirt clings to luminaire surfaces by its stickiness, whereas attracted dirt is held by electrostatic force. Inert dirt varies in accumulation, from practically nothing on vertical surfaces to as much as a horizontal surface holds before the dirt is dislodged by gravity or air circulation. Examples of adhesive dirt are grease from cooking, particles from machine operation borne by oil vapor, particles borne by water vapor as in a laundry, and fumes from metal-pouring operations or plating tanks. Examples of attracted dirt are hair, lint, fibers, and dry particles that are electrostatically charged from machine operations. Examples of inert dirt are nonsticky, uncharged particles such as dry flour, sawdust, and fine cinders. [Figures 9-15](#) and [9-16](#) may be useful for evaluating the atmosphere. [Figure 9-16](#) is intended to evaluate the atmosphere-dirt category. Factors 1 to 5 should be assessed and inserted into the spaces in the table, since they are required to describe the conditions of the space. The "Area Adjacent to Task Area" column represents the area separated from but adjacent to the area in which the luminaire operates (which is the "Area Surrounding Task"). The "Filter Factor" column contains the percentages of dirt allowed to pass from the adjacent atmosphere to the surrounding atmosphere.

The "From Adjacent" column indicates the net amount of such dirt that can pass through. This category might include, for example, an open window with a filter factor of 1.0 (no filtering at all), or an air-conditioning system with a filter factor of 0.1 (90% of dirt is filtered out). The total of all the numbers in the "Subtotal" column is a number up to 60 and can be translated into the applicable atmosphere-dirt category listed at the bottom of the table.

3. From the appropriate luminaire maintenance category curve of [Figure 9-17](#), the applicable dirt condition curve and the proper elapsed time in months of the planned cleaning cycle, the LDD factor is found. For example, if the category is I, the atmosphere is dirty, and cleaning occurs every 20 months, the LDD is approximately 0.80. An alternative procedure to [Figure 9-17](#) is to use the fitted equation

| Maintenance Category | Top Enclosure                                                                                                                                                                                                       | Bottom Enclosure                                                                  |
|----------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|
| I                    | 1. None                                                                                                                                                                                                             | 1. None                                                                           |
| II                   | 1. None<br>2. Transparent with 15 percent or more uplight through apertures<br>3. Translucent with 15 percent or more uplight through apertures<br>4. Opaque with 15 percent or more uplight through apertures      | 1. None<br>2. Louvers or baffles                                                  |
| III                  | 1. Transparent with less than 15 percent upward light through apertures<br>2. Translucent with less than 15 percent upward light through apertures<br>3. Opaque with less than 15 percent uplight through apertures | 1. None<br>2. Louvers or baffles                                                  |
| IV                   | 1. Transparent unapertured<br>2. Translucent unapertured<br>3. Opaque unapertured                                                                                                                                   | 1. None<br>2. Louvers                                                             |
| V                    | 1. Transparent unapertured<br>2. Translucent unapertured<br>3. Opaque unapertured                                                                                                                                   | 1. Transparent unapertured<br>2. Translucent unapertured                          |
| VI                   | 1. None<br>2. Transparent unapertured<br>3. Translucent unapertured<br>4. Opaque unapertured                                                                                                                        | 1. Transparent unapertured<br>2. Translucent unapertured<br>3. Opaque unapertured |

To assist in determining Luminaire Dirt Depreciation (LDD) factors, luminaires are separated into six categories (I through VI). To arrive at categories, luminaires are arbitrarily divided into sections, a Top Enclosure and a Bottom Enclosure, by drawing a horizontal line through the light center of the lamp or lamps. The characteristics listed for the enclosures are then selected as best describing the luminaire. Only one



### Figure 9-14. Procedure for Determining Luminaire Maintenance Categories

\*See step 2 under Luminaire Dirt Depreciation.  
Factors for use in the table are 1: Cleanest conditions imaginable; 2: Clean, but not the cleanest; 3: Average; 4: Dirty, but not the dirtiest; 5: Dirtiest imaginable.

|                       | Very Clean                                                         | Clean                                                                     | Medium                                          | Dirty                                                 |
|-----------------------|--------------------------------------------------------------------|---------------------------------------------------------------------------|-------------------------------------------------|-------------------------------------------------------|
| Generated Dirt        | None                                                               | Very little                                                               | Noticeable but not heavy                        | Accumulates rapidly                                   |
| Ambient Dirt          | None (or none enters area)                                         | Some (almost none enters)                                                 | Some enters area                                | Large amount enters area                              |
| Removal or Filtration | Excellent                                                          | Better than average                                                       | Poorer than average                             | Only fans or blowers if any                           |
| Adhesion              | None                                                               | Slight                                                                    | Enough to be visible after some months          | High—probably due to oil, humidity, or static         |
| Examples              | High grade offices, not near production; laboratories; clean rooms | Offices in older buildings or near production; light assembly; inspection | Mill offices; paper processing; light machining | Heat treating; high-speed printing; rubber processing |

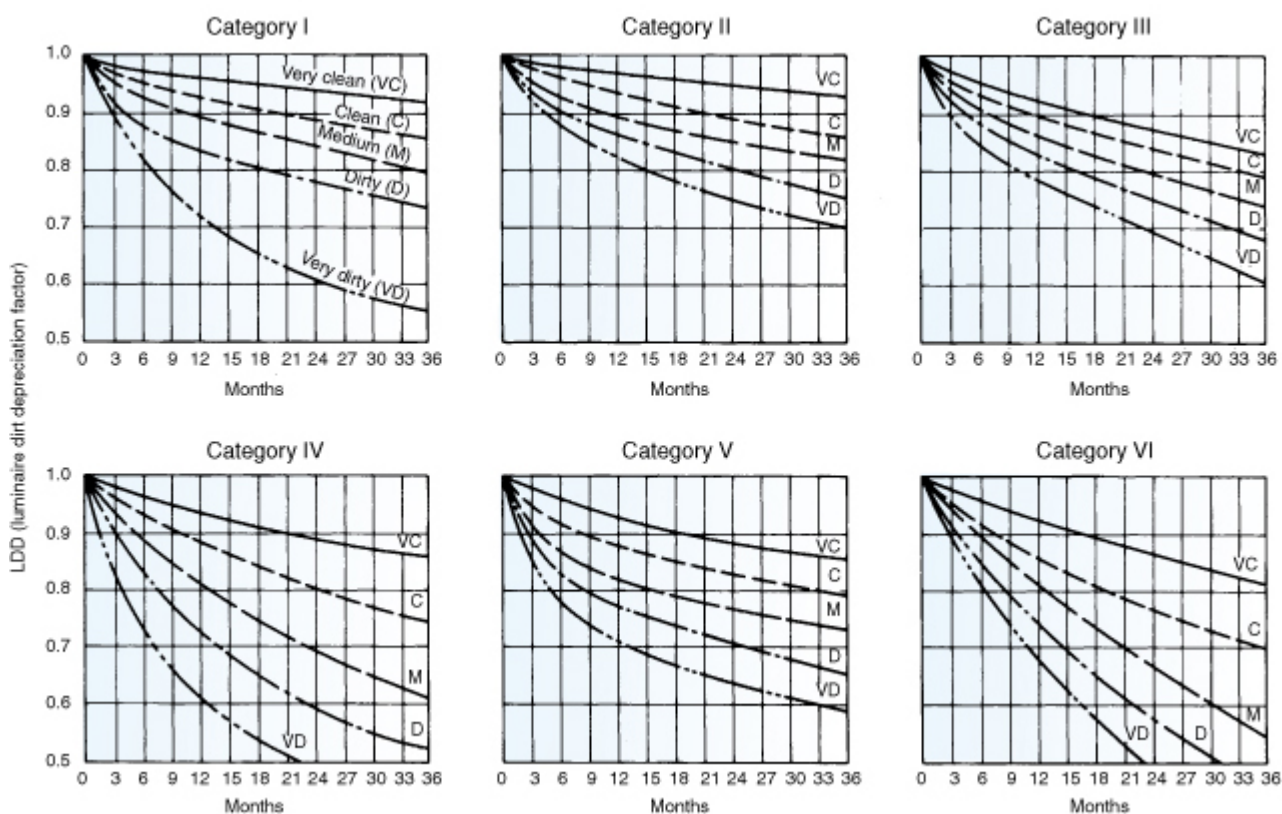
$$LDD = e^{-A_i B} \quad (9-31)$$

where the constants  $A$  and  $B$  are found from [Figure 9-18](#), based on the luminaire maintenance category and the atmosphere condition involved, and  $t$  is time in decimal years (e.g., 1 yr 6 mo is entered as 1.5 yr).

**Room Surface Dirt Depreciation Factor.** The accumulation of dirt on room surfaces reduces the amount of luminous flux reflected and interreflected to the workplane. To take this into account, [Figure 9-19](#) has been developed to provide room surface dirt depreciation (RSDD) factors for use in calculating maintained average illuminance levels. These factors are determined as follows:

1. From one of the five curves in [Figure 9-19](#), find the expected dirt depreciation using [Figure 9-15](#) or 9-16 as a guide to atmospheric dirt conditions, together with an estimate of the time between cleanings. For example, if the atmosphere is dirty and room surfaces are cleaned every 24 months, the expected dirt depreciation is approximately 30%.
2. Knowing the expected dirt depreciation (step 1), the type of luminaire distribution (see [Chapter 7](#), Luminaires) and the room cavity ratio, determine the RSDD factor from [Figure 9-19](#). For example, for a dirt depreciation of 30%, a direct luminaire, and a room cavity ratio (RCR) of 4, the RSDD would be 0.92.

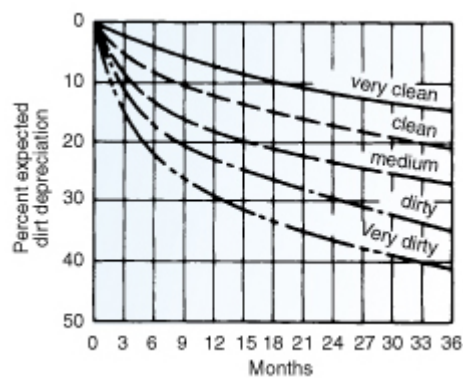
**Lamp Burnout Factor.** Lamp burnouts contribute to light loss. If lamps are not replaced promptly after burnout, the average illuminance is decreased proportionally. In some instances, more than just the faulty lamp may be lost. For example, when series sequence fluorescent ballasts are used and one lamp fails, both lamps go out. The lamp burnout (LBO) factor is the ratio of the number of lamps remaining lighted to the total, for the maximum number of burnouts permitted.



**Figure 9-17.** Luminaire Dirt Depreciation (LDD) factors for six luminaire categories (I through VI) and for five degrees of dirtiness as determined from [Figures 9-14](#) or 9-15.

| Luminaire Maintenance Category | B   | A          |       |        |       |            |
|--------------------------------|-----|------------|-------|--------|-------|------------|
|                                |     | Very Clean | Clean | Medium | Dirty | Very Dirty |
| I                              | .69 | .038       | .071  | .111   | .162  | .301       |
| II                             | .62 | .033       | .068  | .102   | .147  | .188       |
| III                            | .70 | .079       | .106  | .143   | .184  | .236       |
| IV                             | .72 | .070       | .131  | .216   | .314  | .452       |
| V                              | .53 | .078       | .128  | .190   | .249  | .321       |
| VI                             | .88 | .076       | .145  | .218   | .284  | .396       |

**Figure 9-18.** Luminaire Dirt Depreciation Constants Used for Calculating the LDD for Six Luminaire Categories and Five Degrees of Dirtiness



| Percent Expected Dirt Depreciation | Luminaire Distribution Type |     |     |     |             |     |     |     |                 |     |     |     |               |     |     |     |
|------------------------------------|-----------------------------|-----|-----|-----|-------------|-----|-----|-----|-----------------|-----|-----|-----|---------------|-----|-----|-----|
|                                    | Direct                      |     |     |     | Semi-Direct |     |     |     | Direct-Indirect |     |     |     | Semi-Indirect |     |     |     |
|                                    | 10                          | 20  | 30  | 40  | 10          | 20  | 30  | 40  | 10              | 20  | 30  | 40  | 10            | 20  | 30  | 40  |
| Room Cavity Ratio                  |                             |     |     |     |             |     |     |     |                 |     |     |     |               |     |     |     |
| 1                                  | .98                         | .96 | .94 | .92 | .97         | .92 | .89 | .84 | .94             | .87 | .80 | .76 | .94           | .87 | .80 | .76 |
| 2                                  | .98                         | .96 | .94 | .92 | .96         | .92 | .88 | .83 | .94             | .87 | .80 | .75 | .94           | .87 | .79 | .75 |
| 3                                  | .98                         | .95 | .93 | .90 | .96         | .91 | .87 | .82 | .94             | .86 | .79 | .74 | .94           | .86 | .78 | .74 |
| 4                                  | .97                         | .95 | .92 | .90 | .95         | .90 | .85 | .80 | .94             | .86 | .79 | .73 | .94           | .86 | .78 | .74 |
| 5                                  | .97                         | .94 | .91 | .89 | .94         | .90 | .84 | .79 | .93             | .86 | .78 | .72 | .93           | .86 | .77 | .74 |
| 6                                  | .97                         | .94 | .91 | .88 | .94         | .89 | .83 | .78 | .93             | .85 | .78 | .71 | .93           | .85 | .76 | .74 |
| 7                                  | .97                         | .94 | .90 | .87 | .93         | .88 | .82 | .77 | .93             | .84 | .77 | .70 | .93           | .84 | .76 | .74 |
| 8                                  | .96                         | .93 | .89 | .86 | .93         | .87 | .81 | .75 | .93             | .84 | .76 | .69 | .93           | .84 | .76 | .74 |
| 9                                  | .96                         | .92 | .88 | .85 | .93         | .87 | .80 | .74 | .93             | .84 | .76 | .68 | .93           | .84 | .75 | .74 |
| 10                                 | .96                         | .92 | .87 | .83 | .93         | .86 | .79 | .72 | .93             | .84 | .75 | .67 | .92           | .83 | .75 | .74 |

**Figure 9-19.** Room Surface Dirt Depreciation (RSDD) Factors

Manufacturers' mortality statistics should be consulted for the performance of each lamp type to determine the number expected to burn out before the time of planned replacement is reached. In practice, the number of lamp burnouts is a reflection of the quality of the lighting services program.

*Total Light Loss Factor.* The total light loss factor (LLF) is simply the product of all the contributing factors described above. Where factors are not known, or not applicable, they are assumed to be unity. If the total LLF is excessive, it may be desirable to reselect the luminaire.

## STATISTICAL QUANTITIES

When lighting calculations and system modeling are required, it is important that an appropriate method be applied to predict system performance. If an inappropriate model is used, the results can be inaccurate. A designer should therefore have knowledge of the capabilities and limitations of the different modeling options and their applications.

### Averages

An average value is the simplest way of specifying the performance of a lighting system. "Average" usually refers to the mean of several calculated or measured values. The greater the number of values, the more accurate the mean. Grids of calculation or measurement points are usually used, often formed by a rectangular array of rows and columns. Point spacing is determined by the accuracy requirements for the average. The accuracy of an average obtained from a calculation or measurement grid can be estimated by doubling the number of points in the grid and determining the size of the change in the average. A large change may indicate the need for more points. This process can be repeated until the change in the average is small enough to indicate that sufficient accuracy has been attained.

An average can be accurate but not indicative of variation in values. For this reason, the average illuminance (or an average of any other quantity) should be used only when the distribution is expected to be relatively uniform across an area. When a localized lighting system is desired, such as for a reception desk in a lobby, bimodal, or multimodal distributions result, and an average-illuminance calculation method should not be used. An average value can be used to design the system for the general circulation space, but for the task area, individual point source calculations should be used to characterize the task lighting.

In general, an average value alone is not sufficient to fully describe or evaluate lighting system performance. Information on the uniformity of the lighting is also important. The following two subsections consider methods for describing the uniformity of lighting across an area.

### Minima and Maxima

If a large number of analysis points are used for calculation, then the variability of the lighting can be evaluated and the minimum and maximum values can be determined and located. The minima and maxima can be important indicators of the quality of the design, particularly if they deviate significantly from the desired average. In some design situations, maximum and minimum design values may be specified. In evaluating whether or not a particular design is acceptable, it is important to focus on the critical task areas within a space. Minima often occur around the perimeter of a room or lighted area, where tasks may not be located. Levels below the target level may be acceptable if they are not at actual task locations. In other design situations, the maximum value may be critical. For example, it may not be desirable to have room surface luminances that exceed a particular value. This is the case in the lighting recommendations for spaces with visual display terminals (VDTs).

Uniformity is often expressed in terms of a ratio of two quantities. Examples are maximum to minimum, maximum to average, and average to minimum. Different design situations warrant

different uses of these measures.

## Criterion Ratings

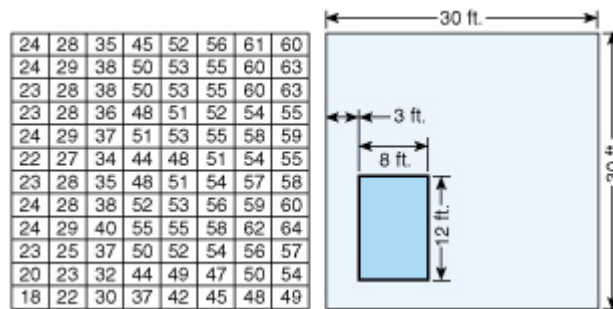
The maximum and minimum values provide little information about the overall distribution of a particular photometric or derived quantity across a space. The criterion rating is a convenient way to obtain greater detail regarding the distribution of a quantity across a space. The criterion rating is the probability that a specific criterion is met or exceeded anywhere within a defined area. It can be used in addition to (or instead of) concepts such as averages and minimum and maximum levels. Lighting criteria to which this technique may be applied include luminance, illuminance, visual comfort probability (VCP), contrast, visibility metrics, and visual performance metrics.

The criterion rating assumes the name of the criterion being rated. For example, the criterion rating for illuminance is called the illuminance rating; for VCP, the VCP rating. Assume, for example, that an illuminance of 500 lx has been established as the design criterion for a space. The illuminance rating defines the likelihood that the illuminance is equal to or greater than 500 lx at any point on the workplane. This criterion rating is determined by evaluating the appropriate quantity (by calculation or measurement) at a grid of points covering the area in question. The distance between evaluation points must not exceed one-fifth the distance from any luminaire to the evaluation plane. The percentage of points that comply with the criterion is the criterion rating:

$$\text{criterion rating} = \frac{(\text{number of points satisfying criterion}) \times 100\%}{\text{number of points computed or measured}} \quad (9-32)$$

Criterion ratings may be expressed using a notation that lists the rating, in percent, followed by the criterion, separated by the symbol @, which stands for "at." For example, a lighting system producing a luminance of 20 cd/m<sup>2</sup> over 60% of the specified area may have its luminance rating expressed as 60%@20 cd/m<sup>2</sup>. For dimensionless criteria, such as contrast and VCP, the shorthand form for the criterion rating must include the name and value of the criteria; for example, 92% @70 VCP means 92% of the area has a VCP of 70 or better. The designer determines the desired coverage area for a particular criterion value.

As an example of the use of the criterion rating technique (using the foot as the unit of length), consider a square room 30 ft on a side, as shown in [Figure 9-20](#), with an 8-ft ceiling height, a 3-ft-high workplane, and recessed luminaires. The tabulated values in [Figure 9-20](#) are calculated illuminances in the 8×12-ft shaded area. The required illuminance is 50 fc in the shaded area. The distance from the workplane to the luminaires is 5 ft (8 ft-3 ft). Thus, the distance between rows and columns of analysis points must be no greater than 1 ft (5 ft/5). To determine the criterion rating, the calculated illuminance values are examined for criterion compliance. It is found that 47 of the 96 locations receive an illuminance of 50 fc or more. The illuminance rating of this lighting system for the shaded area is then 48.9% [(47/96)×100%]. This can be expressed as 48.9%@50 fc.



**Figure 9-20.** Example of criterion rating technique. The numbers in the grid represent the calculated illuminances, in fc, in the center of each ft<sup>2</sup> of the shaded portion of the work plane.

## CALCULATION OF BASIC QUANTITIES

### Illuminance

Illuminance is one of the fundamental quantities used in designing and evaluating lighting systems. To determine the direct illuminance at a point on an area, one must determine that either a point or an area source method is applicable to the situation. To obtain the total illuminance at any point or on any surface, the interreflected component must be appropriately determined and added to the direct component (see Examples 2, 3, and 4 in the section "Examples of Basic Lighting Calculations," in this chapter).

### Luminance

As a primary visual stimulus, luminance is the most important and useful calculated quantity. One of the most common situations in which luminance must be calculated is for the evaluation of visual tasks, such as for print on paper. Methods for evaluating the visual performance or visibility of a task require a value for the task contrast, size and adaptation luminance. The luminances of both the task ( $L_t$ ) and the background ( $L_b$ ) are needed to determine the task contrast. The quantities  $L_t$  and  $L_b$  are specific to a particular task location, lighting condition, and viewer orientation (see Examples 6 and 7 in the section Examples of Basic Lighting Calculations, in this chapter).

Luminance calculations are performed whenever it is necessary to calculate the luminance of a surface that exhibits a directionally sensitive reflectance. A calculation model that computes luminance should be able to predict the luminance at any point. Although it is not required that any given method be able to take all possible ranges of the following nine parameters into account, any restrictions that the method imposes should be adequately noted. Because of the complexity involved in calculating luminance, this calculation is generally performed on a computer.

- Room size and shape
- Room surface reflectances
- Luminaire characteristics
- Number and location of luminaires
- Nature of the given surface



- Observer location, line of sight, and viewing angle
- Nature and luminance of all other surfaces in the environment
- Body shadow effects
- Polarization effects

The luminance at a particular location in a luminous environment is given by

$$L = \int dE(\theta, \psi) f_r(\theta, \psi) \quad (9-33)$$

where

$L$  = luminance at a point on a surface in a particular viewing direction,

$\theta, \psi$  = spherical coordinates, declination, and azimuth, respectively,

$dE(\theta, \psi)$  = differential amount of illuminance at the point in the plane of the surface from a direction indicated by  $(\theta, \psi)$ ,

$f_r(\theta, \psi)$  = bidirectional reflectance distribution function (BRDF) of the surface material for a particular viewing direction.

Figure 9-21 indicates the necessary coordinates. This expression represents the total effect of all components of illuminance multiplied by the appropriate BRDF to give the luminance of the surface. The BRDF is dependent on the surface reflectance characteristics, the viewing angle, and the size of the light source used to measure it.

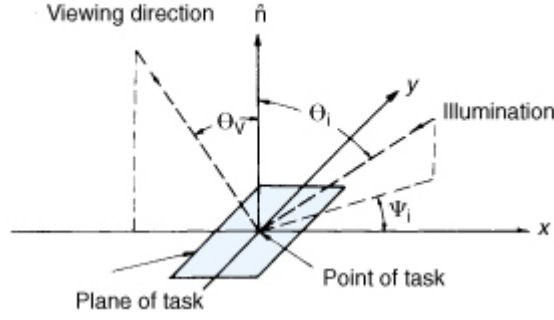
It should be noted that unlike perfectly diffuse reflectances, the BRDF is sensitive to both incident light and viewing directions. This can be expressed as

$$f_r(\theta_v, \psi_v, \theta_i, \psi_i)$$

where the subscript  $i$  represents the incident direction and subscript  $v$  the viewing direction. In many cases only the difference in azimuthal angle between the incident and exitant directions is required. Then the specification of the BRDF becomes

$$f_r(\theta_v, \theta_i, \psi_i)$$

where  $\psi_i$  is the difference in azimuthal angle between the incident and exitant directions. This simplification is not possible for non-axially-isotropic materials such as brushed metal surfaces. In such cases, the azimuthal incident and viewing angles cannot be made relative but must have a fixed orientation with respect to the surface. For many surfaces, however, the simplification can be made and the equation for luminance becomes



**Figure 9-21.** Task and illumination coordinates.

$$L(\theta_v) = \int dE(\theta_i, \psi_i) f_r(\theta_v; \theta_i, \psi_i) \quad (9-34)$$

The viewing angle  $\theta_v$  is normally held constant.

Some surfaces exhibit sensitivity to polarization. It is then possible to separate the BRDF into two orthogonal components associated with orthogonal planes of polarization ( $p_1$  and  $p_2$ ). The BRDFs are

$$f_{rp1}(\theta_v; \theta_i, \psi_i)$$

$$f_{rp2}(\theta_v; \theta_i, \psi_i)$$

In a complementary fashion, two orthogonal components of the illuminance can be considered separately, and are indicated by  $dE_{p1}$  and  $dE_{p2}$ . This gives

$$L(\theta_v) = \int [dE_{p1}(\theta_i, \psi_i) f_{rp1}(\theta_v; \theta_i, \psi_i) + dE_{p2}(\theta_i, \psi_i) f_{rp2}(\theta_v; \theta_i, \psi_i)] \quad (9-35)$$

The expression for  $L$  is general and applicable to all situations. Since the illuminance values and luminance factors must be expressed as analytic functions in order to attempt integration of these expressions, there can be, in general, no closed-form analytic expression for  $L$ . Approximation by the method of finite elements allows an evaluation of the equation. The BRDFs now take the form of a set of discrete values that sample the continuous BRDF. The resulting approximation is

$$L(\theta_v) \approx \sum [\Delta E_{p1}(\theta_i, \psi_i) f_{rp1}(\theta_v; \theta_i, \psi_i) + \Delta E_{p2}(\theta_i, \psi_i) f_{rp2}(\theta_v; \theta_i, \psi_i)] \quad (9-36)$$

The sum is taken over all the discrete values of illuminance. The number of discrete steps determines the accuracy of the approximation. The step size in these approximations is determined by the need to model high gradients of either the illuminance or the BRDFs. In the case of calculations of luminance for visual tasks, a modification can be applied to the BRDF to



take account of a body shadow.

## Exitance

If room surfaces are considered to be lambertian, then the exitances of discrete elements can be found using a flux transfer model described above. Exitance distributions across a room surface can be determined at an array of points that cover it, using lighting analysis software. For rooms with a uniform lighting system, average room surface exitances can be determined using the lumen method (see Example 5 in "Examples of Basic Lighting Calculations," in this chapter).

## CALCULATION OF DERIVED QUANTITIES

From the photometric quantities--illuminance, luminance, and exitance--it is possible to calculate other quantities that characterize how the human visual system interprets or is affected by a visual scene. This section discusses a number of different quantities of this type and provides equations or references for use in their computation.

## Contrast

Contrast represents the difference in luminance between the task detail and its background relative to the luminance of the background or the luminances in the visual scene. There are three different formulas for computing contrast, each of which providing a slightly different answer. See [Chapter 3](#), Vision and Perception, for definitions. See also Example 7 in "Examples of Basic Lighting Calculations," in this chapter.

## Visual Performance and Visibility Metrics

Relative visual performance (RVP) and equivalent sphere illumination (ESI) are metrics for the evaluation of visual performance and visibility, respectively. The calculation of these quantities requires the determination of the task and background luminances (to obtain the task contrast). The task size and adaptation luminance are also needed. The equations needed to compute these quantities are provided in the references for [Chapter 3](#), Vision and Perception, where they are discussed in more detail.

## Visual Comfort Probability (VCP)

Discomfort glare is the sensation of discomfort caused by luminances that are high relative to the average luminance in the field of view. The visual comfort probability (VCP) is the probability that a normal observer does not experience discomfort when viewing a lighting system under defined conditions.

Equations for the calculation of the VCP are derived from correlating photometric and geometric characteristics of simple lighting patterns with discomfort glare assessments of observers.<sup>61-68</sup> Experiments in simulated rooms have been used to confirm the extension from the laboratory to actual lighting installations.<sup>69,70</sup> This system was tested and validated using lensed direct fluorescent systems only. VCP should not be applied to very small sources such as incandescent and high-intensity discharge luminaires, to very large sources such as ceiling and indirect systems, or to nonuniform sources such as parabolic reflectors.

To calculate the VCP<sup>71-81</sup> several intermediate calculations must first be performed. The position index of a source,  $P$ , is an inverse measure of the relative sensitivity to a glare source at different

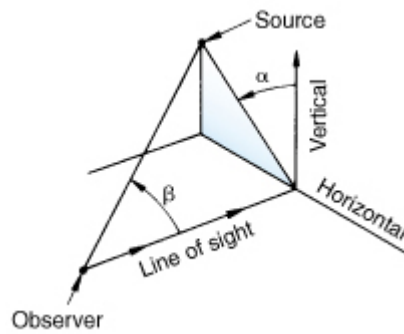
positions throughout the field of view. Selected values or families of curves were published in early references.  $P$  is given by the formula<sup>79</sup>

$$P = \exp[(35.2 - 0.31889\alpha - 1.22e^{-2\alpha/9})10^{-3} \beta + (21 + 0.26667\alpha - 0.002963\alpha^2)10^{-5} \beta^2] \quad (9-40)$$

where

$\alpha$  = angle from vertical of the plane containing the source and the line of sight (Figure 9-22), in degrees,

$\beta$  = angle between the line of sight and the line from the observer to the source.



**Figure 9-22.** Geometry defining position index as used in VCP calculations.

The average luminance for the entire field of view,  $F_v$ , is approximated by the following equation:

$$F_v = \frac{L_w \omega_w + L_f \omega_f + L_c \omega_c + \sum L_s \omega_s}{5} \quad (9-41)$$

where

$L_w$  = average luminance of the walls in  $\text{cd/m}^2$ ,

$L_f$  = average luminance of the floor in  $\text{cd/m}^2$ ,

$L_c$  = average luminance of the ceiling in  $\text{cd/m}^2$ ,

$L_s$  = average luminance of the source in  $\text{cd/m}^2$ ,

$\omega_w$  = solid angle subtended at the observer by the walls in sr,

$\omega_f$  = solid angle subtended at the observer by the floor in sr,

$\omega_c$  = solid angle subtended at the observer by the ceiling in sr,

$\omega_s$  = solid angle subtended at the observer by the source in sr.

The 5 in the denominator arises from the assumption that the total field of view is 5 sr.<sup>79</sup>

A function  $Q$  has been developed for use in the calculation of the VCP. This function is given by

$$Q = 20.4\omega_s + 1.52\omega_s^{0.2} - 0.075 \quad (9-42)$$

where  $\omega_s$  is the solid angle subtended at the observer by the source, in steradians. The values of  $P$ ,  $F_v$ , and  $Q$  are used to determine the index of sensation,  $M$ :

$$M = \frac{0.50L_s Q}{PF_v^{0.44}} \quad (9-43)$$

The luminance in the above equation is expressed in  $\text{cd/m}^2$ . The factor 0.50 in the numerator allows for the use of these units.

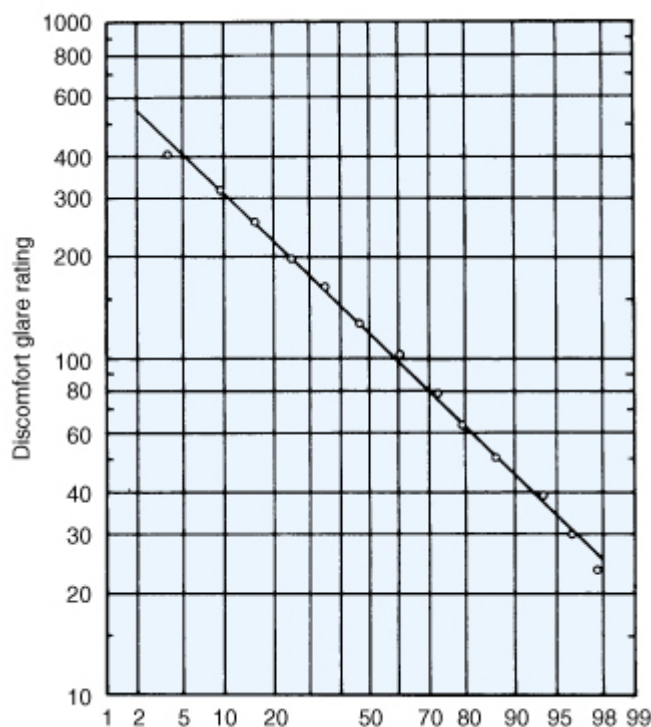
From the index of sensation of each source, a discomfort glare rating (DGR) can be calculated for the full field of view. The DGR is a metric of discomfort that increases as discomfort increases; it is also used in calculating the VCP. It is given by

$$\text{DGR} = \left( \sum_{i=1}^n M_i \right) n^{-0.0914} \quad (9-44)$$

where

$n$  = number of sources in the field of view,  
 $M_i$  = index of sensation for the  $i$ th source.

The relation between DGR and VCP may be found from a graph such as [Figure 9-23](#) or may be calculated by<sup>80</sup>



**Figure 9-23.** A chart for converting discomfort glare ratings (DGR) to VCP (the percentage of observers expected to judge a given lighting condition to be either comfortable or at the borderline between comfort and discomfort).

$$\text{VCP} = \frac{100}{\sqrt{2\pi}} \int_{-\infty}^{6.374 - 1.3227 \ln \text{DGR}} e^{-t^2/2} dt \quad (9-45)$$

These basic relations may be applied through a variety of techniques. Generally, the room cavity concept is used, in which the actual ceiling and floor luminances and solid angles are replaced by their equivalent cavity values. The computation can be performed by summing throughout the enclosure.<sup>81</sup>

VCP values are frequently associated with luminaires under standardized conditions of use. In this method, the luminaires are fractionally apportioned over the ceiling according to a standard scheme. VCP values are determined for:<sup>71,74,76</sup>

1. An initial average horizontal illuminance of 1000 lx (100 fc)
2. Room reflectances of  $\rho_{CC} = 0.80$ ,  $\rho_W = 0.50$ , and  $\rho_{FC} = 0.20$
3. Luminaire mounting heights above the floor of 2.6, 3, 4, and 4.9 m (8.5, 10, 13, and 16 ft)
4. A (given) range of room dimensions including square, long narrow, and short wide rooms
5. An observation point 1.2 m (4 ft) in front of the center of the rear wall and 1.2 m (4 ft) above the floor
6. A horizontal line of sight, directly forward
7. An upward limit to the field of view corresponding to an angle of  $53^\circ$  above and directly forward from the observer

There are two objectives in applying the standardized procedure. First, it simplifies calculations by permitting organization of various procedural steps. Second, it allows comparisons between those luminaires for which the standardized values have been tabulated even before a specific lighting layout has been made. [Figure 9-24](#) illustrates a typical tabulation of visual comfort probabilities as developed by the standardized procedure.

## Unified Glare Rating (UGR)

The CIE has recently developed a unified glare rating (UGR) system. This system is intended for discomfort glare prediction and is likely to be adopted by many nations. The IESNA is currently considering UGR for future recommendations. UGR is calculated from

$$\text{UGR} = 8 \log_{10} \left( \frac{0.25}{L_b} \right) \sum_i \frac{L_i^2 \omega_i}{P_i^2}$$

where

$L_b$  = luminance of the field of view, in  $\text{cd/m}^2$ , not including luminaire luminance,

$L$  = luminance of a luminaire in the direction of the observer,

$\omega$  = solid angle of a luminaire subtended to the observer,

$P$  = position index of luminaire.

This formula is limited to those situations where  $0.0003 \leq \omega \leq 0.1$ . Values of UGR range from 5 to 30, with higher numbers indicating greater discomfort glare.

## Average Illuminance Calculation: The Lumen Method

The lumen method is used in calculating the average illuminance  $\bar{E}$  on the workplane in an interior. This is defined as

$$\bar{E} = \frac{\text{total flux onto workplane}}{\text{workplane area}} \quad (9-46)$$

A coefficient of utilization (CU) gives the fraction of lamp lumens that reach the workplane, directly from sources and from interreflections. The CU takes into account the efficiency of the luminaire and the impact of the luminaire distribution and the room surfaces in its derivation. Thus the number of lumens produced by the lamps, multiplied by this CU, determines the number that reaches the workplane:

| Room |     | Luminaires Lengthwise |      |      |      | Luminaires Crosswise |      |      |      |
|------|-----|-----------------------|------|------|------|----------------------|------|------|------|
| W    | L   | 8.5                   | 10.0 | 13.0 | 16.0 | 8.5                  | 10.0 | 13.0 | 16.0 |
| 20   | 20  | 78                    | 82   | 90   | 94   | 77                   | 81   | 89   | 93   |
| 20   | 30  | 73                    | 76   | 82   | 88   | 72                   | 75   | 81   | 86   |
| 20   | 40  | 71                    | 73   | 78   | 82   | 70                   | 72   | 76   | 80   |
| 20   | 60  | 69                    | 71   | 74   | 78   | 68                   | 70   | 73   | 76   |
| 30   | 20  | 78                    | 82   | 88   | 92   | 77                   | 81   | 87   | 92   |
| 30   | 30  | 73                    | 75   | 80   | 85   | 72                   | 74   | 79   | 84   |
| 30   | 40  | 70                    | 72   | 75   | 78   | 69                   | 71   | 74   | 77   |
| 30   | 60  | 68                    | 69   | 71   | 74   | 67                   | 69   | 70   | 73   |
| 30   | 80  | 67                    | 69   | 69   | 72   | 67                   | 68   | 68   | 71   |
| 40   | 20  | 79                    | 82   | 87   | 92   | 79                   | 82   | 87   | 91   |
| 40   | 30  | 74                    | 76   | 79   | 84   | 73                   | 75   | 78   | 83   |
| 40   | 40  | 71                    | 72   | 74   | 77   | 70                   | 71   | 73   | 76   |
| 40   | 60  | 68                    | 69   | 70   | 72   | 68                   | 69   | 69   | 71   |
| 40   | 80  | 67                    | 68   | 68   | 70   | 67                   | 68   | 67   | 69   |
| 40   | 100 | 67                    | 68   | 67   | 69   | 67                   | 67   | 66   | 68   |
| 60   | 30  | 75                    | 76   | 79   | 83   | 74                   | 76   | 78   | 82   |
| 60   | 40  | 71                    | 72   | 74   | 76   | 71                   | 72   | 73   | 76   |
| 60   | 60  | 69                    | 69   | 69   | 71   | 68                   | 69   | 68   | 70   |
| 60   | 80  | 68                    | 68   | 67   | 69   | 67                   | 68   | 66   | 68   |
| 60   | 100 | 67                    | 67   | 66   | 67   | 67                   | 67   | 65   | 66   |
| 100  | 40  | 74                    | 75   | 75   | 78   | 74                   | 74   | 75   | 77   |
| 100  | 60  | 71                    | 71   | 71   | 72   | 71                   | 71   | 70   | 72   |

|     |     |    |    |    |    |    |    |    |    |
|-----|-----|----|----|----|----|----|----|----|----|
| 100 | 80  | 70 | 70 | 68 | 69 | 70 | 69 | 67 | 69 |
| 100 | 100 | 69 | 68 | 66 | 67 | 69 | 68 | 66 | 67 |

---

This example is for use when the units of length and illuminance are the foot (ft) and footcandle (fc). VCP values are identical if units of length and illuminance are the meter (m) and the lux (lx).

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Wall Reflectance, 50%; Effective Ceiling Cavity Reflectance, 80%; Effective Floor Cavity Reflectance, 20%; Luminaire No. 000; Workplane Illuminance, 100 fc

**Figure 9-24.** Example of a Tabulation of VCP Values

$$\bar{E}_{\text{initial}} = \frac{(\text{total lamp lumens}) \times \text{CU}}{\text{workplane area}} \quad (9-47)$$

Since the design objective usually is maintained illuminance, a light loss factor must be applied to allow for the estimated depreciation in lamp lumens over time, the estimated losses from dirt collection on the luminaire surfaces (including lamps), and other factors that affect luminaire lumen output over time. The formula thus becomes

$$\bar{E}_{\text{maintained}} = \frac{(\text{total lamp lumens}) \times \text{CU} \times \text{LLF}}{\text{workplane area}} \quad (9-48)$$

where

CU = coefficient of utilization,  
LLF = light loss factor.

Although design calculations are based on the LLF using both nonrecoverable and recoverable factors, it is sometimes necessary to calculate illuminance in a new lighting installation. In such cases, repeat the calculation using the nonrecoverable losses, since the recoverable losses do not occur at 100 hours, the time at which lamps are nominally at rated lumens.

The lamp lumens in the formula are most conveniently taken as the total rated lamp lumens in the luminaires:

$$\bar{E}_{\text{maintained}} = \frac{(\text{number of luminaires}) \times (\text{lamps per luminaire}) \times (\text{lamp lumens}) \times \text{CU} \times \text{LLF}}{\text{workplane area}} \quad (9-49)$$

If the desired maintained illuminance is known, this equation can be solved for the total number of luminaires needed:

$$\begin{aligned} & \text{number of luminaires} \\ &= \frac{\overline{E}_{\text{maintained}} \times (\text{workplane area})}{(\text{lamps per luminaire}) \times (\text{lamp lumens}) \times \text{CU} \times \text{LLF}} \end{aligned} \quad (9-50)$$

For a typical form for calculating illuminance, see [Figure 9-25](#).

**Limitations.** The illuminance computed by the lumen method is an average value that is representative only if the luminaires are spaced to obtain reasonably uniform illuminance. The calculation of the coefficients of utilization is based on empty interiors having surfaces that exhibit perfectly diffuse reflectance. The average illuminance determined by the lumen method is defined to be the total lumens reaching the workplane divided by the area of the workplane. The average value determined this way might vary considerably from that obtained by averaging discrete values of illuminance at several points.

**Calculation Procedure.** [Figure 9-25](#) provides a procedure for calculating average maintained illuminance using the zonal-cavity method.<sup>44-46</sup>

**Cavity Ratios.** The radiative exchange between the top and the base of a rectangular space is a function of the proportions of its length, width, and height. Cavity ratio values approximate this effect by combining these proportions into a single quantity.

In the zonal-cavity method, the effects of room proportions, luminaire suspension length, and workplane height upon the coefficient of utilization are respectively represented by the room cavity ratio, ceiling cavity ratio, and floor cavity ratio. These ratios are determined by dividing the room into three cavities, as shown by [Figure 9-26](#), and substituting dimensions (in m or ft) into the following formula:

$$\text{cavity ratio} = \frac{5h(\text{cavity length} + \text{cavity width})}{\text{cavity length} \times \text{cavity width}} \quad (9-51)$$

where

$$h = \begin{cases} h_{\text{RC}} & \text{for the room cavity ratio (RCR)} \\ h_{\text{CC}} & \text{for the ceiling cavity ratio (CCR)} \\ h_{\text{FC}} & \text{for the floor cavity ratio (FCR)} \end{cases}$$

The illuminance in rooms of irregular shape can be determined by calculating the room cavity ratio using the following formula and solving the problem in the usual manner:

$$\begin{aligned} & \text{cavity ratio} \\ &= \frac{2.5 \times (\text{cavity height}) \times (\text{cavity perimeter})}{\text{area of cavity base}} \end{aligned} \quad (9-52)$$

**Effective Cavity Reflectances.** [Figure 9-27](#) provides a means of converting the combination of wall and ceiling or wall and floor reflectances into a single effective ceiling cavity reflectance,

$\rho_{CC}$  and a single effective floor cavity reflectance,  $\rho_{FC}$ . In lumen method calculations, the ceiling, wall, and floor reflectances should be initial values. The RSDD factor compensates for the decrease of reflectance with time. Note that for surface-mounted and recessed luminaires, the CCR equals 0 and the actual ceiling reflectance may be used for  $\rho_{CC}$ .

A rectangular cavity consists of four walls, each having a reflectance of  $\rho_W$ , and a base of reflectance  $\rho_B$  (ceiling or floor reflectance). The effective reflectance,  $\rho_{eff}$  of this cavity is the ratio of the flux reflected out to the flux entering the cavity through its opening. If the reflectances are assumed to be perfectly diffuse and the flux is assumed to enter the cavity in a perfectly diffuse way, it is possible to calculate the effective cavity reflectance using flux transfer theory. The result is

$$\rho_{eff} = \frac{\rho_B \rho_W f \left( 2 \frac{A_B}{A_W} (1-f) - f \right) + \rho_B f^2 + \rho_W \frac{A_B}{A_W} (1-f)^2}{1 - \rho_B \rho_W \frac{A_B}{A_W} (1-f)^2 - \rho_W \left( 1 - 2 \frac{A_B}{A_W} (1-f) \right)}$$

(9-53)

where

$A_B, A_W$  = areas of the cavity base and walls, respectively,

$\rho_B, \rho_W$  = reflectances of the cavity base and walls, respectively,

$f$  = form factor between the cavity opening and the cavity base.

### GENERAL INFORMATION

Project identification: \_\_\_\_\_  
(Give name of area and/or building and room number)

Average maintained illuminance for design: \_\_\_\_\_ lux or  
\_\_\_\_\_ footcandles

Lamp data:

Type and color: \_\_\_\_\_

Luminaire data:

Manufacturer: \_\_\_\_\_

Number per luminaire: \_\_\_\_\_

Catalog number: \_\_\_\_\_

Total lumens per luminaire: \_\_\_\_\_

### SELECTION OF COEFFICIENT OF UTILIZATION

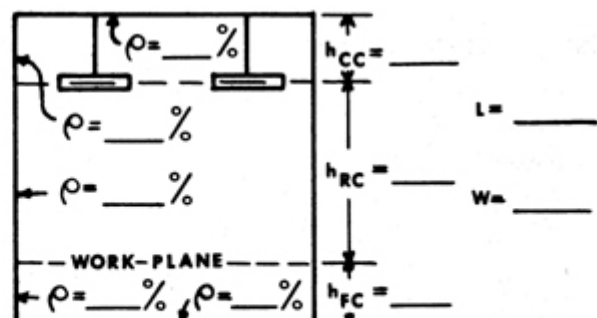
Step 1: Fill in sketch at right

Step 2: Determine Cavity Ratios

Room Cavity Ratio, RCR = \_\_\_\_\_

Ceiling Cavity Ratio, CCR = \_\_\_\_\_

Floor Cavity Ratio, FCR = \_\_\_\_\_



Step 3: Obtain Effective Ceiling Cavity Reflectance ( $\rho_{CC}$ )

$\rho_{CC}$  = \_\_\_\_\_



Step 4: Obtain Effective Floor Cavity Reflectance ( $\rho_{FC}$ )

$\rho_{FC} =$  \_\_\_\_\_

Step 5: Obtain Coefficient of Utilization (CU) from Manufacturer's Data

CU = \_\_\_\_\_

### SELECTION OF LIGHT LOSS FACTORS

#### Nonrecoverable

Luminaire ambient temperature \_\_\_\_\_

Voltage to luminaire \_\_\_\_\_

Ballast factor \_\_\_\_\_

Luminaire surface depreciation \_\_\_\_\_

#### Recoverable

Room surface dirt depreciation \_\_\_\_\_

RSDD \_\_\_\_\_

Lamp lumen depreciation \_\_\_\_\_

LLD \_\_\_\_\_

Lamp burnouts factor \_\_\_\_\_

LBO \_\_\_\_\_

Luminaire dirt depreciation \_\_\_\_\_

LDD \_\_\_\_\_

Total light loss factor, LLF (product of individual factors above) = \_\_\_\_\_

### CALCULATIONS

(Average Maintained Illuminance)

$$\text{Number of Luminaires} = \frac{(\text{Illuminance}) \times (\text{Area})}{(\text{Lumens per Luminaire}) \times (\text{CU}) \times (\text{LLF})}$$

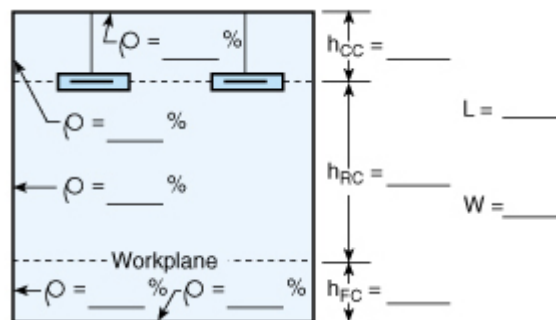
= \_\_\_\_\_ =

$$\text{Illuminance} = \frac{(\text{Number of Luminaires}) \times (\text{Lumens per Luminaire}) \times (\text{CU}) \times (\text{LLF})}{(\text{Area})}$$

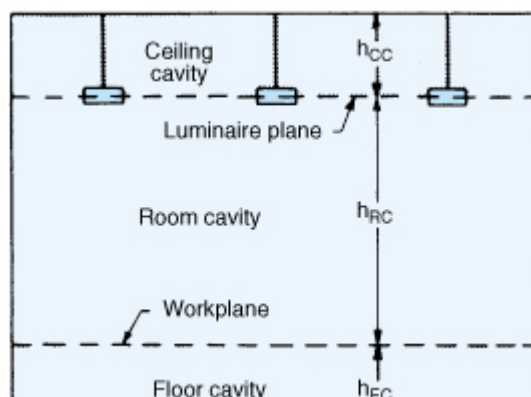
= \_\_\_\_\_ =

Calculated by: \_\_\_\_\_ Date: \_\_\_\_\_

**Fig. 9-20.** Average illuminance calculation sheet



**Figure 9-25.** Average illuminance calculation sheet.





**Figure 9-26.** The three cavities used in the zonal-cavity method.

The form factor  $f$  in the above equation is given by

$$\begin{aligned}
 f = & \frac{2}{\pi xy} \ln \left( \frac{(1+x^2)(1+y^2)}{1+x^2+y^2} \right)^{1/2} \\
 & + \frac{2}{\pi x} (1+x^2)^{1/2} \arctan \left( \frac{y}{(1+x^2)^{1/2}} \right) \\
 & + \frac{2}{\pi y} (1+y^2)^{1/2} \arctan \left( \frac{x}{(1+y^2)^{1/2}} \right) \\
 & - \frac{2}{\pi x} \arctan y - \frac{2}{\pi y} \arctan x \quad (9-54)
 \end{aligned}$$

where  $x$  and  $y$  have the following values:

$$x = \frac{\text{cavity length}}{\text{cavity depth}} \quad (9-55a)$$

$$y = \frac{\text{cavity length}}{\text{cavity depth}} \quad (9-55b)$$

The arctangents are expressed in radians. If it is assumed that the cavity is square, then

$$x = y = \frac{10}{\text{cavity ratio}} \quad (9-56)$$

The effective ceiling cavity reflectance of nonhorizontal ceilings can be determined by the following formula. The illuminance problem is then solved in the usual manner:

$$\rho_{CC} = \frac{\rho}{\frac{A_s}{A_o} - \rho \left( \frac{A_s}{A_o} - 1 \right)} \quad (9-57)$$

where

$A_o$  = area of the ceiling opening,

$A_s$  = area of the ceiling surface,

$\rho$  = reflectance of the ceiling surface.

The formula for  $\rho_{CC}$  applies to concave ceilings such as a hemispherical dome where all parts of

the ceiling are exposed to all other parts. If the ceiling surface reflectance is not the same for all parts of the ceiling, an area-weighted average should be used. Thus, if the ceiling has  $n$  sections, then

$$\rho = \frac{\sum_{i=1}^n \rho_i A_i}{\sum_{i=1}^n A_i} \quad (9-58)$$

where

$\rho_i$  = reflectance of the  $i$ th section of the ceiling,

$A_i$  = area of the  $i$ th section of the ceiling.

| Percent Base† Reflectance | 90 |    |    |    |    |    |    |    |    |    | 80 |    |    |    |    |    |    |    |    |    | 70 |    |    |    |    |    |    |    |    |    |
|---------------------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Percent Wall Reflectance  | 90 | 80 | 70 | 60 | 50 | 40 | 30 | 20 | 10 | 0  | 90 | 80 | 70 | 60 | 50 | 40 | 30 | 20 | 10 | 0  | 90 | 80 | 70 | 60 | 50 | 40 | 30 | 20 | 10 | 0  |
| Cavity Ratio              |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 0.2                       | 89 | 88 | 88 | 87 | 86 | 85 | 85 | 84 | 84 | 82 | 79 | 78 | 78 | 77 | 77 | 76 | 76 | 75 | 74 | 72 | 70 | 69 | 68 | 68 | 67 | 67 | 66 | 66 | 65 | 64 |
| 0.4                       | 88 | 87 | 86 | 85 | 84 | 83 | 81 | 80 | 79 | 76 | 79 | 77 | 76 | 75 | 74 | 73 | 72 | 71 | 70 | 68 | 69 | 68 | 67 | 66 | 65 | 64 | 63 | 62 | 61 | 58 |
| 0.6                       | 87 | 86 | 84 | 82 | 80 | 79 | 77 | 76 | 74 | 73 | 78 | 76 | 75 | 73 | 71 | 70 | 68 | 66 | 65 | 63 | 69 | 67 | 65 | 64 | 63 | 61 | 59 | 58 | 57 | 54 |
| 0.8                       | 87 | 85 | 82 | 80 | 77 | 75 | 73 | 71 | 69 | 67 | 78 | 75 | 73 | 71 | 69 | 67 | 65 | 63 | 61 | 57 | 68 | 66 | 64 | 62 | 60 | 58 | 56 | 55 | 53 | 50 |
| 1.0                       | 86 | 83 | 80 | 77 | 75 | 72 | 69 | 66 | 64 | 62 | 77 | 74 | 72 | 69 | 67 | 65 | 62 | 60 | 57 | 55 | 68 | 65 | 62 | 60 | 58 | 55 | 53 | 52 | 50 | 47 |
| 1.2                       | 85 | 82 | 78 | 75 | 72 | 69 | 66 | 63 | 60 | 57 | 76 | 73 | 70 | 67 | 64 | 61 | 58 | 55 | 53 | 51 | 67 | 64 | 61 | 59 | 57 | 54 | 50 | 48 | 46 | 44 |
| 1.4                       | 85 | 80 | 77 | 73 | 69 | 65 | 62 | 59 | 57 | 52 | 76 | 72 | 68 | 65 | 62 | 59 | 55 | 53 | 50 | 48 | 67 | 63 | 60 | 58 | 55 | 51 | 47 | 45 | 44 | 41 |
| 1.6                       | 84 | 79 | 75 | 71 | 67 | 63 | 59 | 56 | 53 | 50 | 75 | 71 | 67 | 63 | 60 | 57 | 53 | 50 | 47 | 44 | 67 | 62 | 59 | 56 | 53 | 47 | 45 | 43 | 41 | 38 |
| 1.8                       | 83 | 78 | 73 | 69 | 64 | 60 | 56 | 53 | 50 | 48 | 75 | 70 | 66 | 62 | 58 | 54 | 50 | 47 | 44 | 41 | 66 | 61 | 58 | 54 | 51 | 46 | 42 | 40 | 38 | 35 |
| 2.0                       | 83 | 77 | 72 | 67 | 62 | 56 | 53 | 50 | 47 | 43 | 74 | 69 | 64 | 60 | 56 | 52 | 48 | 45 | 41 | 38 | 66 | 60 | 56 | 52 | 49 | 45 | 40 | 38 | 36 | 33 |
| 2.2                       | 82 | 76 | 70 | 65 | 59 | 54 | 50 | 47 | 44 | 40 | 74 | 68 | 63 | 58 | 54 | 49 | 45 | 42 | 38 | 35 | 66 | 60 | 55 | 51 | 48 | 43 | 38 | 36 | 34 | 32 |
| 2.4                       | 82 | 75 | 69 | 64 | 58 | 53 | 48 | 45 | 41 | 37 | 73 | 67 | 61 | 56 | 52 | 47 | 43 | 40 | 36 | 33 | 65 | 60 | 54 | 50 | 46 | 41 | 37 | 35 | 32 | 30 |
| 2.6                       | 81 | 74 | 67 | 62 | 56 | 51 | 46 | 42 | 38 | 35 | 73 | 66 | 60 | 55 | 50 | 45 | 41 | 38 | 34 | 31 | 65 | 59 | 54 | 49 | 45 | 40 | 35 | 33 | 30 | 28 |
| 2.8                       | 81 | 73 | 66 | 60 | 54 | 49 | 44 | 40 | 36 | 34 | 73 | 65 | 59 | 53 | 48 | 43 | 39 | 36 | 32 | 29 | 65 | 59 | 53 | 48 | 43 | 38 | 33 | 30 | 28 | 26 |
| 3.0                       | 80 | 72 | 64 | 58 | 52 | 47 | 42 | 38 | 34 | 30 | 72 | 65 | 58 | 52 | 47 | 42 | 37 | 34 | 30 | 27 | 64 | 58 | 52 | 47 | 42 | 37 | 32 | 29 | 27 | 24 |
| 3.2                       | 79 | 71 | 63 | 56 | 50 | 45 | 40 | 36 | 32 | 28 | 72 | 65 | 57 | 51 | 45 | 40 | 35 | 33 | 28 | 25 | 64 | 58 | 51 | 46 | 40 | 36 | 31 | 28 | 25 | 23 |
| 3.4                       | 79 | 70 | 62 | 54 | 48 | 43 | 38 | 34 | 30 | 27 | 71 | 64 | 56 | 49 | 44 | 39 | 34 | 32 | 27 | 24 | 64 | 57 | 50 | 45 | 39 | 35 | 29 | 27 | 24 | 22 |
| 3.6                       | 78 | 69 | 61 | 53 | 47 | 42 | 36 | 32 | 28 | 25 | 71 | 63 | 54 | 48 | 43 | 38 | 32 | 30 | 25 | 23 | 63 | 56 | 49 | 44 | 38 | 33 | 28 | 25 | 22 | 20 |
| 3.8                       | 78 | 69 | 60 | 51 | 45 | 40 | 35 | 31 | 27 | 23 | 70 | 62 | 53 | 47 | 41 | 36 | 31 | 28 | 24 | 22 | 63 | 56 | 49 | 43 | 37 | 32 | 27 | 24 | 21 | 19 |
| 4.0                       | 77 | 69 | 58 | 51 | 44 | 39 | 33 | 29 | 25 | 22 | 70 | 61 | 53 | 46 | 40 | 35 | 30 | 26 | 22 | 20 | 63 | 55 | 48 | 42 | 36 | 31 | 26 | 23 | 20 | 17 |
| 4.2                       | 77 | 62 | 57 | 50 | 43 | 37 | 32 | 28 | 24 | 21 | 69 | 60 | 52 | 45 | 39 | 34 | 29 | 25 | 21 | 18 | 62 | 55 | 47 | 41 | 35 | 30 | 25 | 22 | 19 | 16 |
| 4.4                       | 76 | 61 | 56 | 49 | 42 | 36 | 31 | 27 | 23 | 20 | 69 | 60 | 51 | 44 | 38 | 33 | 28 | 24 | 20 | 17 | 62 | 54 | 46 | 40 | 34 | 29 | 24 | 21 | 18 | 15 |
| 4.6                       | 76 | 60 | 55 | 47 | 40 | 35 | 30 | 26 | 22 | 19 | 69 | 59 | 50 | 43 | 37 | 32 | 27 | 23 | 19 | 15 | 62 | 53 | 45 | 39 | 33 | 28 | 24 | 21 | 17 | 14 |
| 4.8                       | 75 | 59 | 54 | 46 | 39 | 34 | 28 | 25 | 21 | 18 | 68 | 58 | 49 | 42 | 36 | 31 | 26 | 22 | 18 | 14 | 62 | 53 | 45 | 38 | 32 | 27 | 23 | 20 | 16 | 13 |
| 5.0                       | 75 | 59 | 53 | 45 | 38 | 33 | 28 | 24 | 20 | 16 | 68 | 58 | 48 | 41 | 35 | 30 | 25 | 21 | 18 | 14 | 61 | 52 | 44 | 36 | 31 | 26 | 22 | 19 | 16 | 12 |
| 6.0                       | 73 | 61 | 49 | 41 | 34 | 29 | 24 | 20 | 16 | 11 | 66 | 55 | 44 | 38 | 31 | 27 | 22 | 19 | 15 | 10 | 60 | 51 | 41 | 35 | 28 | 24 | 19 | 16 | 13 | 09 |
| 7.0                       | 70 | 58 | 45 | 38 | 30 | 27 | 21 | 18 | 14 | 08 | 64 | 53 | 41 | 35 | 28 | 24 | 19 | 16 | 12 | 07 | 58 | 43 | 38 | 32 | 26 | 22 | 17 | 14 | 11 | 06 |
| 8.0                       | 68 | 55 | 42 | 35 | 27 | 23 | 18 | 15 | 12 | 06 | 62 | 50 | 38 | 32 | 25 | 21 | 17 | 14 | 11 | 05 | 57 | 46 | 35 | 29 | 23 | 19 | 15 | 13 | 10 | 05 |
| 9.0                       | 66 | 52 | 38 | 31 | 25 | 21 | 16 | 14 | 11 | 05 | 61 | 49 | 36 | 30 | 23 | 19 | 15 | 13 | 10 | 04 | 56 | 45 | 33 | 27 | 21 | 18 | 14 | 12 | 09 | 04 |
| 10.0                      | 65 | 51 | 36 | 29 | 22 | 19 | 15 | 11 | 09 | 04 | 59 | 46 | 33 | 27 | 21 | 18 | 14 | 11 | 08 | 03 | 55 | 43 | 31 | 25 | 19 | 16 | 12 | 10 | 08 | 03 |

\* Values in this table are based on a length to width ratio of 1.6.

† Ceiling, floor, or floor of cavity.

Figure 9-27. *Continued\**

| Percent Base† Reflectance | 40 |    |    |    |    |    |    |    |    |    | 30 |    |    |    |    |    |    |    |    |    | 20 |    |    |    |    |    |    |    |    |    |
|---------------------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Percent Wall Reflectance  | 90 | 80 | 70 | 60 | 50 | 40 | 30 | 20 | 10 | 0  | 90 | 80 | 70 | 60 | 50 | 40 | 30 | 20 | 10 | 0  | 90 | 80 | 70 | 60 | 50 | 40 | 30 | 20 | 10 | 0  |
| Cavity Ratio              |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 0.2                       | 40 | 40 | 39 | 39 | 39 | 38 | 38 | 37 | 36 | 36 | 31 | 31 | 30 | 30 | 29 | 29 | 29 | 28 | 28 | 27 | 21 | 20 | 20 | 20 | 20 | 20 | 19 | 19 | 19 | 17 |
| 0.4                       | 41 | 40 | 39 | 39 | 38 | 37 | 36 | 35 | 34 | 34 | 31 | 31 | 30 | 30 | 29 | 28 | 28 | 27 | 26 | 25 | 22 | 21 | 20 | 20 | 20 | 19 | 19 | 18 | 18 | 16 |
| 0.6                       | 41 | 40 | 39 | 38 | 37 | 36 | 34 | 33 | 32 | 31 | 32 | 31 | 30 | 29 | 28 | 27 | 26 | 26 | 25 | 23 | 23 | 21 | 21 | 20 | 19 | 19 | 18 | 18 | 17 | 15 |
| 0.8                       | 41 | 40 | 38 | 37 | 36 | 35 | 33 | 32 | 31 | 29 | 32 | 31 | 30 | 29 | 28 | 26 | 25 | 25 | 23 | 22 | 24 | 22 | 21 | 20 | 19 | 19 | 18 | 17 | 16 | 14 |
| 1.0                       | 42 | 40 | 38 | 37 | 35 | 33 | 32 | 31 | 29 | 27 | 33 | 32 | 30 | 29 | 27 | 25 | 24 | 23 | 22 | 20 | 25 | 23 | 22 | 20 | 19 | 18 | 17 | 16 | 15 | 13 |
| 1.2                       | 42 | 40 | 38 | 36 | 34 | 32 | 30 | 29 | 27 | 25 | 33 | 32 | 30 | 28 | 27 | 25 | 23 | 22 | 21 | 19 | 25 | 23 | 22 | 20 | 19 | 17 | 17 | 16 | 14 | 12 |
| 1.4                       | 42 | 39 | 37 | 35 | 33 | 31 | 29 | 27 | 25 | 23 | 34 | 32 | 30 | 28 | 26 | 24 | 22 | 21 | 19 | 18 | 26 | 24 | 22 | 20 | 18 | 17 | 16 | 15 | 13 | 12 |
| 1.6                       | 42 | 39 | 37 | 35 | 32 | 30 | 27 | 25 | 23 | 22 | 34 | 33 | 29 | 27 | 25 | 23 | 22 | 20 | 18 | 17 | 26 | 24 | 22 | 20 | 18 | 17 | 16 | 15 | 13 | 11 |
| 1.8                       | 42 | 39 | 36 | 34 | 31 | 29 | 26 | 24 | 22 | 21 | 35 | 33 | 29 | 27 | 25 | 23 | 21 | 19 | 17 | 16 | 27 | 25 | 23 | 20 | 18 | 17 | 15 | 14 | 12 | 10 |
| 2.0                       | 42 | 39 | 36 | 34 | 31 | 28 | 25 | 23 | 21 | 19 | 35 | 33 | 29 | 26 | 24 | 22 | 20 | 18 | 16 | 14 | 28 | 25 | 23 | 20 | 18 | 16 | 15 | 13 | 11 | 09 |
| 2.2                       | 42 | 39 | 36 | 33 | 30 | 27 | 24 | 22 | 19 | 18 | 36 | 32 | 29 | 26 | 24 | 22 | 19 | 17 | 15 | 13 | 28 | 25 | 23 | 20 | 18 | 16 | 14 | 12 | 10 | 09 |
| 2.4                       | 43 | 39 | 35 | 33 | 29 | 27 | 24 | 21 | 18 | 17 | 36 | 32 | 29 | 26 | 24 | 22 | 19 | 16 | 14 | 12 | 29 | 26 | 23 | 20 | 18 | 16 | 14 | 12 | 10 | 08 |
| 2.6                       | 43 | 39 | 35 | 32 | 29 | 26 | 23 | 20 | 17 | 15 | 36 | 32 | 29 | 25 | 23 | 21 | 18 | 16 | 14 | 12 | 29 | 26 | 23 | 20 | 18 | 16 | 14 | 11 | 09 | 08 |
| 2.8                       | 43 | 39 | 35 | 32 | 28 | 25 | 22 | 19 | 16 | 14 | 37 | 33 | 29 | 25 | 23 | 21 | 17 | 15 | 13 | 11 | 30 | 27 | 23 | 20 | 18 | 15 | 13 | 11 | 09 | 07 |
| 3.0                       | 43 | 39 | 35 | 31 | 27 | 24 | 21 | 18 | 16 | 13 | 37 | 33 | 29 | 25 | 22 | 20 | 17 | 15 | 12 | 10 | 30 | 27 | 23 | 20 | 17 | 15 | 13 | 11 | 09 | 07 |
| 3.2                       | 43 | 39 | 35 | 31 | 27 | 23 | 20 | 17 | 15 | 13 | 37 | 33 | 29 | 25 | 22 | 19 | 16 | 14 | 12 | 10 | 31 | 27 | 23 | 20 | 17 | 15 | 12 | 11 | 09 | 06 |
| 3.4                       | 43 | 39 | 34 | 30 | 26 | 23 | 20 | 17 | 14 | 12 | 37 | 33 | 29 | 25 | 22 | 19 | 16 | 14 | 11 | 09 | 31 | 27 | 23 | 20 | 17 | 15 | 12 | 10 | 08 | 06 |
| 3.6                       | 44 | 39 | 34 | 30 | 26 | 22 | 19 | 16 | 14 | 11 | 38 | 33 | 29 | 24 | 21 | 18 | 15 | 13 | 10 | 09 | 32 | 27 | 23 | 20 | 17 | 15 | 12 | 10 | 08 | 05 |
| 3.8                       | 44 | 38 | 33 | 29 | 25 | 22 | 18 | 16 | 13 | 10 | 38 | 33 | 28 | 24 | 21 | 18 | 15 | 13 | 10 | 08 | 32 | 28 | 23 | 20 | 17 | 15 | 12 | 10 | 07 | 05 |
| 4.0                       | 44 | 38 | 33 | 29 | 25 | 21 | 18 | 15 | 12 | 10 | 38 | 33 | 28 | 24 | 21 | 18 | 14 | 12 | 09 | 07 | 33 | 28 | 23 | 20 | 17 | 14 | 11 | 09 | 07 | 05 |
| 4.2                       | 44 | 38 | 33 | 29 | 24 | 21 | 17 | 15 | 12 | 10 | 38 | 33 | 28 | 24 | 20 | 17 | 14 | 12 | 09 | 07 | 33 | 28 | 23 | 20 | 17 | 14 | 11 | 09 | 07 | 04 |
| 4.4                       | 44 | 38 | 33 | 28 | 24 | 20 | 17 | 14 | 11 | 09 | 39 | 33 | 28 | 24 | 20 | 17 | 14 | 11 | 09 | 06 | 34 | 28 | 24 | 20 | 17 | 14 | 11 | 09 | 07 | 04 |
| 4.6                       | 44 | 38 | 32 | 28 | 23 | 19 | 16 | 14 | 11 | 08 | 39 | 33 | 28 | 24 | 20 | 17 | 13 | 10 | 08 | 06 | 34 | 29 | 24 | 20 | 17 | 14 | 11 | 09 | 07 | 04 |
| 4.8                       | 44 | 38 | 32 | 27 | 22 | 19 | 16 | 13 | 10 | 08 | 39 | 33 | 28 | 24 | 20 | 17 | 13 | 10 | 08 | 05 | 35 | 29 | 24 | 20 | 17 | 13 | 10 | 08 | 06 | 04 |
| 5.0                       | 45 | 38 | 31 | 27 | 22 | 19 | 15 | 13 | 10 | 07 | 39 | 33 | 28 | 24 | 19 | 16 | 13 | 10 | 08 | 05 | 35 | 29 | 24 | 20 | 16 | 13 | 10 | 08 | 06 | 04 |
| 6.0                       | 44 | 37 | 30 | 25 | 20 | 17 | 13 | 11 | 08 | 05 | 39 | 33 | 27 | 23 | 18 | 15 | 11 | 09 | 06 | 04 | 36 | 30 | 24 | 20 | 16 | 13 | 10 | 08 | 05 | 02 |
| 7.0                       | 44 | 36 | 29 | 24 | 19 | 16 | 12 | 10 | 07 | 04 | 40 | 33 | 26 | 22 | 17 | 14 | 10 | 08 | 05 | 03 | 36 | 30 | 24 | 20 | 15 | 12 | 03 | 07 | 04 | 02 |
| 8.0                       | 44 | 35 | 28 | 23 | 18 | 15 | 11 | 09 | 06 | 03 | 40 | 33 | 26 | 21 | 16 | 13 | 09 | 07 | 04 | 02 | 37 | 30 | 23 | 19 | 15 | 12 | 08 | 06 | 03 | 01 |
| 9.0                       | 44 | 35 | 26 | 21 | 16 | 13 | 10 | 08 | 05 | 02 | 40 | 33 | 25 | 20 | 15 | 12 | 09 | 07 | 04 | 02 | 37 | 29 | 23 | 19 | 14 | 11 | 08 | 06 | 03 | 01 |
| 10.0                      | 43 | 34 | 25 | 20 | 15 | 12 | 08 | 07 | 05 | 02 | 40 | 32 | 24 | 19 | 14 | 11 | 08 | 06 | 03 | 01 | 37 | 29 | 22 | 18 | 13 | 10 | 07 | 05 | 03 | 01 |

\* Values in this table are based on a length to width ratio of 1.6.

†Ceiling, floor, or floor of cavity.

**Figure 9-27.** Percent Effective Ceiling or Floor Cavity Reflectances for Various Reflectance Combinations\*

**Luminaire Coefficients of Utilization.** Absorption of light in a luminaire is taken into account in the computation of coefficient of utilization (CU) for that luminaire. Figure 9-28 is a tabulation of coefficients of utilization calculated by the zonal-cavity method for representative luminaire types. These coefficients are for an effective floor cavity reflectance of 20%, but any CU obtained from the table may be corrected for a different value of  $\rho_{FC}$  by applying the appropriate multiplier from Figure 9-29.

Figure 9-28 is based on generic luminaires that can be readily identified. As an example, there are many variations of the flat-bottom fluorescent troffer using prismatic lenses. The luminaires in [Figure 9-28](#) are not to be considered as recommended luminaires. The entries for some present useful data even though the luminaires concerned are no longer commonly used. For example, luminaire 2 is largely out of use; however, the coefficients apply to any indirect luminaire of similar efficiency and direct component, since they do not depend on the shape of the upward intensity distribution. An important feature of these coefficients is that the performance of luminaires of similar distributions but different efficiencies may also be analyzed with their use by making a simple multiplicative correction (see note 3 of [Figure 9-28](#)).

Since the light loss factor includes the effect of dirt deposited on wall surfaces, the selection of the proper column of wall reflectances,  $\rho_w$ , should be based on the initial values expected. The wall reflectance should also represent the weighted average of the reflectances of the painted areas, fenestration or daylight controls, chalkboards, shelves, and so forth in the area to be lighted. The weighting should be based on the relative areas of each type of surface within the cavity being considered. In using [Figure 9-29](#), it is often necessary to interpolate between room cavity ratios and effective ceiling cavity reflectances. This is most easily accomplished by interpolating first between RCRs to obtain CUs for effective ceiling cavity reflectances that straddle the actual  $\rho_{CC}$ , and then interpolating between these CUs.

### Instructions and Notes: Tables of Coefficients of Utilization ([Figure 9-28](#))

1. The luminaires in this table are organized by source type and luminaire form rather than by application, for convenience in locating luminaires. In some cases, the data are based on an actual luminaire; in other cases, they represent a composite of generic luminaire types. Therefore, whenever possible, specific luminaire data should be used in preference to those in this table.
2. The polar intensity sketch (intensity distribution curve) and the corresponding luminaire spacing criterion are representative of many luminaires of each type shown. A specific luminaire may differ in perpendicular-plane (crosswise) and parallel-plane (lengthwise) intensity distributions and in spacing criterion from the values shown. However, the various coefficients depend only on the average intensity at each polar angle from nadir. The average intensity values used to generate the coefficients are given at the end of the table, normalized to 1000 lamp lumens for reference.
3. The various coefficients depend only on the average intensity distribution curve and are linearly related to the total luminaire efficiency. Consequently, the tabulated coefficients can be applied to luminaires with similarly shaped average intensity distributions along with a correcting multiplier equal to the new luminaire total efficiency divided by the tabulated luminaire total efficiency. The use of polarizing lenses on fluorescent luminaires has no effect on the coefficients given in this table except as they affect the total luminaire efficiency.
4. Satisfactory installations depend on many factors, including the environment, space utilization, and luminous criteria, as well as the luminaire itself. Consequently, a definitive spacing recommendation cannot be assigned to the luminaire as such. The spacing criterion (SC) values given are only general guides. SC values are not assigned to semi-indirect and indirect luminaires, since the basis of this technique does not apply to such situations. Also, SC values are not given for those bat-wing luminaires that must be located by criteria other than that of horizontal illuminance.

5. Key:

$\rho_{CC}$  = ceiling cavity reflectance (percent),

$\rho_W$  = wall reflectance (percent),

$\rho_{FC}$  = floor cavity reflectance (percent),

RCR = room cavity ratio,

WDRC = wall direct radiation coefficient,

SC = luminaire spacing criterion,

NA = not applicable.

6. Many of the luminaires in this figure appeared in earlier editions of the IESNA *Lighting Handbook*. The identifying number may be different due to a reordering of the luminaires. In some cases, the data have been modified in view of more recent or more extensive information. The user should specifically refer to this edition of the *Lighting Handbook* when referencing luminaires.

7. Fluorescent lamp luminaire efficiencies, and consequently the coefficients, are a function of the number of lamps in relation to the size of the luminaire. This is due to temperature changes and to changes in the blocking of light. In this figure, fluorescent lamp luminaires have been chosen with typical luminaire sizes and numbers of lamps; these are identified under the typical luminaire drawings. Variations of the coefficients with size and number of lamps depend on the many details of luminaire construction. The following correction factors are average values to apply to a four-lamp luminaire 610 mm (2 ft) wide:

| No. of lamps | Width, mm | Width, ft | Multiply by |
|--------------|-----------|-----------|-------------|
| 8            | 1220      | 4         | 1.05        |
| 3            | 610       | 2         | 1.05        |
| 2            | 610       | 2         | 1.1         |
| 2            | 300       | 1         | 0.9         |

Multiply the entries for two-lamp wraparound luminaires by 0.95 for four lamps.

8. Photometric data for fluorescent lamp luminaires in this table are based on tests using standard-wattage fluorescent lamps. Reduced-wattage fluorescent lamps cause lower lamp operating temperatures with some luminaires. Consequently, the efficiency and coefficients may be slightly increased. It is desirable to obtain specific correction factors from the manufacturers. Typical factors for reduced-wattage fluorescent lamps (approximately 10% below standard lamp wattages) are as follows:

| Luminaire                                  | Multiply by |
|--------------------------------------------|-------------|
| 2-lamp strip, surface mounted              | 1.03        |
| 4-lamp troffer, enclosed, non-air-handling | 1.07        |
| 4-lamp wraparound, surface mounted         | 1.07        |
| 2-lamp industrial, vented                  | 1.00        |

Electronic ballasts can be designed for any arbitrary operating condition. The manufacturer must be consulted for specific data.

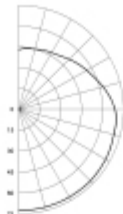
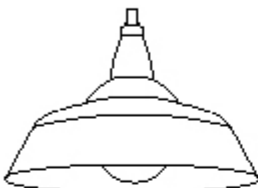
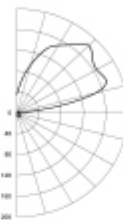
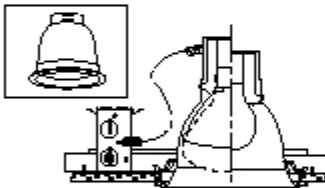
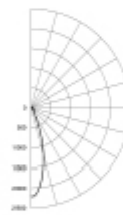
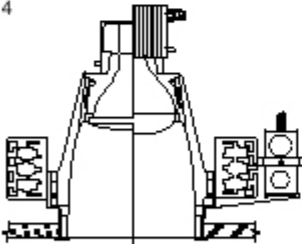
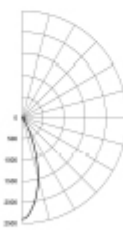
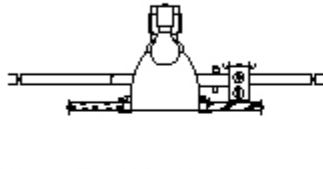
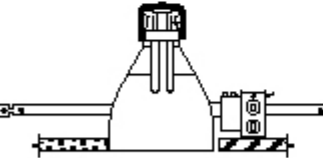
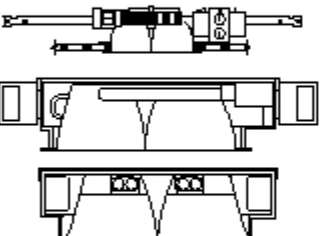
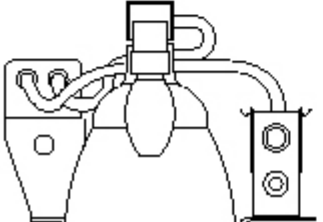
| Typical Luminaire                                           | Typical Intensity Distribution                                                      | Typical Intensity Distribution                                                      |                                                                         |      |              |      |      |              |      |      |                                    |      |      |      |      |    |
|-------------------------------------------------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------|------|--------------|------|------|--------------|------|------|------------------------------------|------|------|------|------|----|
|                                                             |                                                                                     | pcc →                                                                               |                                                                         |      | 80           |      |      | 70           |      |      | 50                                 |      |      | 30   |      |    |
|                                                             |                                                                                     | ρw →                                                                                |                                                                         |      | 70           | 50   | 30   | 70           | 50   | 30   | 50                                 | 30   | 10   | 50   | 30   | 10 |
| RCR ↓                                                       |                                                                                     | EFF = 80.5%                                                                         |                                                                         |      | % DN = 55.9% |      |      | % UP = 44.1% |      |      | Lamp = 150A211F SC (along, across) |      |      |      |      |    |
| 1                                                           |    |    | 0                                                                       | 0.87 | 0.87         | 0.87 | 0.81 | 0.81         | 0.81 | 0.70 | 0.70                               | 0.70 | 0.59 | 0.59 | 0.59 |    |
|                                                             |                                                                                     |                                                                                     | 1                                                                       | 0.76 | 0.71         | 0.66 | 0.70 | 0.66         | 0.61 | 0.56 | 0.52                               | 0.50 | 0.46 | 0.44 | 0.42 |    |
|                                                             |                                                                                     |                                                                                     | 2                                                                       | 0.68 | 0.60         | 0.53 | 0.62 | 0.55         | 0.50 | 0.47 | 0.42                               | 0.38 | 0.39 | 0.35 | 0.32 |    |
|                                                             |                                                                                     |                                                                                     | 3                                                                       | 0.61 | 0.52         | 0.44 | 0.56 | 0.48         | 0.41 | 0.40 | 0.35                               | 0.31 | 0.33 | 0.29 | 0.26 |    |
|                                                             |                                                                                     |                                                                                     | 4                                                                       | 0.55 | 0.45         | 0.37 | 0.51 | 0.42         | 0.35 | 0.35 | 0.30                               | 0.25 | 0.29 | 0.25 | 0.22 |    |
|                                                             |                                                                                     |                                                                                     | 5                                                                       | 0.51 | 0.40         | 0.32 | 0.46 | 0.37         | 0.30 | 0.31 | 0.25                               | 0.21 | 0.26 | 0.21 | 0.18 |    |
|                                                             |                                                                                     |                                                                                     | 6                                                                       | 0.46 | 0.35         | 0.28 | 0.42 | 0.33         | 0.26 | 0.28 | 0.22                               | 0.18 | 0.23 | 0.19 | 0.16 |    |
|                                                             |                                                                                     |                                                                                     | 7                                                                       | 0.43 | 0.32         | 0.25 | 0.39 | 0.29         | 0.23 | 0.25 | 0.20                               | 0.16 | 0.21 | 0.16 | 0.13 |    |
|                                                             |                                                                                     |                                                                                     | 8                                                                       | 0.40 | 0.29         | 0.22 | 0.36 | 0.27         | 0.20 | 0.23 | 0.17                               | 0.14 | 0.19 | 0.15 | 0.12 |    |
|                                                             |                                                                                     |                                                                                     | 9                                                                       | 0.37 | 0.26         | 0.19 | 0.34 | 0.24         | 0.18 | 0.21 | 0.16                               | 0.12 | 0.17 | 0.13 | 0.10 |    |
|                                                             |                                                                                     |                                                                                     | 10                                                                      | 0.34 | 0.24         | 0.17 | 0.32 | 0.22         | 0.16 | 0.19 | 0.14                               | 0.11 | 0.16 | 0.12 | 0.08 |    |
| Pendant diffusing sphere with incandescent lamp             |                                                                                     |                                                                                     |                                                                         |      |              |      |      |              |      |      |                                    |      |      |      |      |    |
| 2                                                           |    |    | EFF = 86.5% % DN = 4.0% % UP = 96.0% Lamp = 100A21/5 SC (along, across) |      |              |      |      |              |      |      |                                    |      |      |      |      |    |
|                                                             |                                                                                     |                                                                                     | 0                                                                       | 0.99 | 0.99         | 0.99 | 0.97 | 0.97         | 0.97 | 0.93 | 0.93                               | 0.93 | 0.89 | 0.89 | 0.88 |    |
|                                                             |                                                                                     |                                                                                     | 1                                                                       | 0.91 | 0.87         | 0.84 | 0.89 | 0.85         | 0.82 | 0.82 | 0.79                               | 0.77 | 0.79 | 0.76 | 0.74 |    |
|                                                             |                                                                                     |                                                                                     | 2                                                                       | 0.83 | 0.76         | 0.70 | 0.80 | 0.74         | 0.69 | 0.71 | 0.67                               | 0.63 | 0.69 | 0.65 | 0.62 |    |
|                                                             |                                                                                     |                                                                                     | 3                                                                       | 0.75 | 0.66         | 0.59 | 0.73 | 0.65         | 0.59 | 0.62 | 0.57                               | 0.53 | 0.60 | 0.55 | 0.52 |    |
|                                                             |                                                                                     |                                                                                     | 4                                                                       | 0.69 | 0.58         | 0.51 | 0.67 | 0.57         | 0.50 | 0.55 | 0.49                               | 0.44 | 0.53 | 0.48 | 0.44 |    |
|                                                             |                                                                                     |                                                                                     | 5                                                                       | 0.63 | 0.52         | 0.44 | 0.61 | 0.51         | 0.44 | 0.49 | 0.43                               | 0.38 | 0.47 | 0.42 | 0.37 |    |
|                                                             |                                                                                     |                                                                                     | 6                                                                       | 0.58 | 0.46         | 0.39 | 0.56 | 0.46         | 0.38 | 0.44 | 0.38                               | 0.33 | 0.43 | 0.37 | 0.33 |    |
|                                                             |                                                                                     |                                                                                     | 7                                                                       | 0.53 | 0.42         | 0.34 | 0.52 | 0.41         | 0.34 | 0.40 | 0.33                               | 0.29 | 0.39 | 0.33 | 0.28 |    |
|                                                             |                                                                                     |                                                                                     | 8                                                                       | 0.50 | 0.38         | 0.31 | 0.48 | 0.37         | 0.31 | 0.36 | 0.30                               | 0.26 | 0.35 | 0.30 | 0.25 |    |
|                                                             |                                                                                     |                                                                                     | 9                                                                       | 0.46 | 0.35         | 0.28 | 0.45 | 0.34         | 0.28 | 0.33 | 0.27                               | 0.23 | 0.32 | 0.27 | 0.22 |    |
|                                                             |                                                                                     |                                                                                     | 10                                                                      | 0.43 | 0.32         | 0.25 | 0.42 | 0.32         | 0.25 | 0.31 | 0.25                               | 0.21 | 0.30 | 0.24 | 0.21 |    |
| Porcelain-enamelled ventilated standard dome with inc. lamp |                                                                                     |                                                                                     |                                                                         |      |              |      |      |              |      |      |                                    |      |      |      |      |    |
| 3                                                           |  |  | EFF = 100% % DN = 100% % UP = 0% Lamp = 150PAR3 SC (along, across)      |      |              |      |      |              |      |      |                                    |      |      |      |      |    |
|                                                             |                                                                                     |                                                                                     | 0                                                                       | 1.20 | 1.20         | 1.20 | 1.17 | 1.17         | 1.17 | 1.12 | 1.12                               | 1.12 | 1.07 | 1.07 | 1.07 |    |
|                                                             |                                                                                     |                                                                                     | 1                                                                       | 1.14 | 1.11         | 1.08 | 1.11 | 1.08         | 1.06 | 1.04 | 1.02                               | 1.00 | 1.01 | 0.99 | 0.97 |    |
|                                                             |                                                                                     |                                                                                     | 2                                                                       | 1.08 | 1.02         | 0.98 | 1.05 | 1.01         | 0.97 | 0.97 | 0.94                               | 0.91 | 0.94 | 0.92 | 0.89 |    |
|                                                             |                                                                                     |                                                                                     | 3                                                                       | 1.02 | 0.95         | 0.90 | 1.00 | 0.94         | 0.89 | 0.91 | 0.87                               | 0.84 | 0.89 | 0.85 | 0.82 |    |
|                                                             |                                                                                     |                                                                                     | 4                                                                       | 0.97 | 0.89         | 0.83 | 0.95 | 0.88         | 0.83 | 0.86 | 0.81                               | 0.78 | 0.84 | 0.80 | 0.77 |    |
|                                                             |                                                                                     |                                                                                     | 5                                                                       | 0.92 | 0.84         | 0.78 | 0.91 | 0.83         | 0.77 | 0.81 | 0.76                               | 0.72 | 0.79 | 0.75 | 0.72 |    |
|                                                             |                                                                                     |                                                                                     | 6                                                                       | 0.88 | 0.79         | 0.73 | 0.87 | 0.78         | 0.73 | 0.77 | 0.72                               | 0.68 | 0.75 | 0.71 | 0.68 |    |
|                                                             |                                                                                     |                                                                                     | 7                                                                       | 0.84 | 0.75         | 0.69 | 0.83 | 0.74         | 0.69 | 0.73 | 0.68                               | 0.64 | 0.72 | 0.67 | 0.64 |    |
|                                                             |                                                                                     |                                                                                     | 8                                                                       | 0.81 | 0.71         | 0.66 | 0.80 | 0.71         | 0.65 | 0.70 | 0.65                               | 0.61 | 0.69 | 0.64 | 0.61 |    |
|                                                             |                                                                                     |                                                                                     | 9                                                                       | 0.78 | 0.68         | 0.62 | 0.77 | 0.68         | 0.62 | 0.67 | 0.62                               | 0.58 | 0.66 | 0.61 | 0.58 |    |
|                                                             |                                                                                     |                                                                                     | 10                                                                      | 0.75 | 0.65         | 0.60 | 0.74 | 0.65         | 0.59 | 0.64 | 0.59                               | 0.56 | 0.63 | 0.59 | 0.56 |    |
| Bare lamp PAR-38 flood                                      |                                                                                     |                                                                                     |                                                                         |      |              |      |      |              |      |      |                                    |      |      |      |      |    |
| 4                                                           |  |  | EFF = 66.2% % DN = 100 % UP = 0 Lamp = 150PAR3 SC (along, across)       |      |              |      |      |              |      |      |                                    |      |      |      |      |    |
|                                                             |                                                                                     |                                                                                     | 0                                                                       | 1.10 | 1.10         | 1.10 | 1.07 | 1.07         | 1.07 | 1.02 | 1.02                               | 1.02 | 0.98 | 0.98 | 0.98 |    |
|                                                             |                                                                                     |                                                                                     | 1                                                                       | 1.06 | 1.03         | 1.02 | 1.03 | 1.01         | 1.00 | 0.98 | 0.96                               | 0.95 | 0.94 | 0.93 | 0.92 |    |
|                                                             |                                                                                     |                                                                                     | 2                                                                       | 1.02 | 0.98         | 0.95 | 1.00 | 0.96         | 0.94 | 0.94 | 0.91                               | 0.89 | 0.91 | 0.89 | 0.88 |    |
|                                                             |                                                                                     |                                                                                     | 3                                                                       | 0.98 | 0.93         | 0.90 | 0.96 | 0.92         | 0.89 | 0.90 | 0.87                               | 0.85 | 0.88 | 0.85 | 0.83 |    |
|                                                             |                                                                                     |                                                                                     | 4                                                                       | 0.94 | 0.89         | 0.85 | 0.93 | 0.88         | 0.84 | 0.86 | 0.83                               | 0.80 | 0.84 | 0.82 | 0.79 |    |
|                                                             |                                                                                     |                                                                                     | 5                                                                       | 0.91 | 0.85         | 0.81 | 0.90 | 0.84         | 0.80 | 0.83 | 0.79                               | 0.77 | 0.81 | 0.78 | 0.76 |    |
|                                                             |                                                                                     |                                                                                     | 6                                                                       | 0.88 | 0.81         | 0.77 | 0.87 | 0.81         | 0.77 | 0.80 | 0.76                               | 0.73 | 0.78 | 0.75 | 0.73 |    |
|                                                             |                                                                                     |                                                                                     | 7                                                                       | 0.85 | 0.78         | 0.74 | 0.84 | 0.78         | 0.74 | 0.77 | 0.73                               | 0.70 | 0.76 | 0.72 | 0.70 |    |
|                                                             |                                                                                     |                                                                                     | 8                                                                       | 0.82 | 0.75         | 0.71 | 0.81 | 0.75         | 0.71 | 0.74 | 0.70                               | 0.68 | 0.73 | 0.70 | 0.67 |    |
|                                                             |                                                                                     |                                                                                     | 9                                                                       | 0.79 | 0.72         | 0.68 | 0.78 | 0.72         | 0.68 | 0.71 | 0.68                               | 0.65 | 0.70 | 0.67 | 0.65 |    |
|                                                             |                                                                                     |                                                                                     | 10                                                                      | 0.77 | 0.70         | 0.66 | 0.76 | 0.69         | 0.65 | 0.69 | 0.65                               | 0.63 | 0.68 | 0.65 | 0.62 |    |
| PAR-38 Flood with spec. anodized reflector (45 deg. cutoff) |                                                                                     |                                                                                     |                                                                         |      |              |      |      |              |      |      |                                    |      |      |      |      |    |
| 5                                                           |  |  | EFF = 66.2% % DN = 100 % UP = 0 Lamp = 150PAR3 SC (along, across)       |      |              |      |      |              |      |      |                                    |      |      |      |      |    |
|                                                             |                                                                                     |                                                                                     | 0                                                                       | 0.79 | 0.79         | 0.79 | 0.77 | 0.77         | 0.77 | 0.74 | 0.74                               | 0.74 | 0.70 | 0.70 | 0.70 |    |
|                                                             |                                                                                     |                                                                                     | 1                                                                       | 0.76 | 0.75         | 0.73 | 0.75 | 0.73         | 0.72 | 0.71 | 0.70                               | 0.69 | 0.68 | 0.68 | 0.67 |    |
|                                                             |                                                                                     |                                                                                     | 2                                                                       | 0.74 | 0.71         | 0.69 | 0.72 | 0.70         | 0.68 | 0.68 | 0.67                               | 0.65 | 0.66 | 0.65 | 0.64 |    |
|                                                             |                                                                                     |                                                                                     | 3                                                                       | 0.71 | 0.68         | 0.66 | 0.70 | 0.67         | 0.65 | 0.66 | 0.64                               | 0.62 | 0.64 | 0.63 | 0.61 |    |
|                                                             |                                                                                     |                                                                                     | 4                                                                       | 0.69 | 0.65         | 0.63 | 0.68 | 0.65         | 0.62 | 0.63 | 0.61                               | 0.60 | 0.62 | 0.60 | 0.58 |    |
|                                                             |                                                                                     |                                                                                     | 5                                                                       | 0.67 | 0.63         | 0.60 | 0.66 | 0.62         | 0.60 | 0.61 | 0.59                               | 0.57 | 0.60 | 0.58 | 0.57 |    |
|                                                             |                                                                                     |                                                                                     | 6                                                                       | 0.65 | 0.61         | 0.58 | 0.64 | 0.60         | 0.58 | 0.59 | 0.57                               | 0.55 | 0.59 | 0.57 | 0.55 |    |
|                                                             |                                                                                     |                                                                                     | 7                                                                       | 0.63 | 0.59         | 0.56 | 0.62 | 0.58         | 0.56 | 0.57 | 0.55                               | 0.53 | 0.57 | 0.55 | 0.53 |    |
|                                                             |                                                                                     |                                                                                     | 8                                                                       | 0.61 | 0.57         | 0.54 | 0.60 | 0.56         | 0.54 | 0.56 | 0.53                               | 0.52 | 0.55 | 0.53 | 0.52 |    |
|                                                             |                                                                                     |                                                                                     | 9                                                                       | 0.59 | 0.55         | 0.52 | 0.59 | 0.55         | 0.52 | 0.54 | 0.52                               | 0.50 | 0.54 | 0.51 | 0.50 |    |
|                                                             |                                                                                     |                                                                                     | 10                                                                      | 0.58 | 0.53         | 0.51 | 0.57 | 0.53         | 0.50 | 0.53 | 0.50                               | 0.49 | 0.52 | 0.50 | 0.48 |    |
| PAR-38 Flood with black baffle                              |                                                                                     |                                                                                     |                                                                         |      |              |      |      |              |      |      |                                    |      |      |      |      |    |



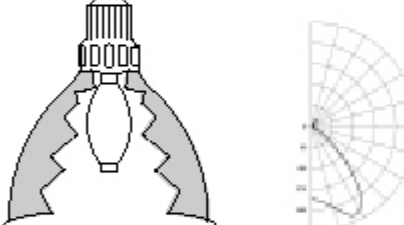
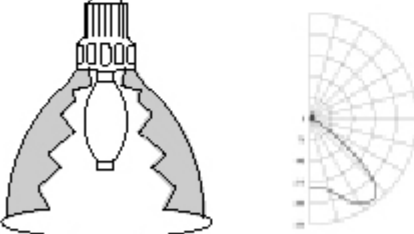
Figure 9-28 Continued

| Typical Luminaire                                                                                                                                                   | Typical Intensity Distribution | $\rho_{cc} \rightarrow$ | 80                   |             |      | 70          |             |      | 50        |                                       |      | 30                                    |      |  |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------|-------------------------|----------------------|-------------|------|-------------|-------------|------|-----------|---------------------------------------|------|---------------------------------------|------|--|
|                                                                                                                                                                     |                                |                         | $\rho_w \rightarrow$ |             |      |             |             |      |           |                                       |      |                                       |      |  |
|                                                                                                                                                                     |                                | RCR<br>$\downarrow$     | EFF = 96.2%          |             |      | % DN = 100% |             |      | % UP = 0% |                                       |      | Lamp = 150A21II<br>SC (along, across) |      |  |
| <div>6</div> <div></div> <div>A-lamp downlight with spec. anodized reflector</div> | 0                              | 0.82                    | 0.82                 | 0.82        | 0.81 | 0.81        | 0.81        | 0.77 | 0.77      | 0.77                                  | 0.74 | 0.74                                  | 0.74 |  |
|                                                                                                                                                                     | 1                              | 0.78                    | 0.76                 | 0.75        | 0.77 | 0.75        | 0.73        | 0.72 | 0.71      | 0.70                                  | 0.70 | 0.68                                  | 0.66 |  |
|                                                                                                                                                                     | 2                              | 0.74                    | 0.71                 | 0.68        | 0.73 | 0.70        | 0.67        | 0.67 | 0.65      | 0.63                                  | 0.65 | 0.63                                  | 0.61 |  |
|                                                                                                                                                                     | 3                              | 0.70                    | 0.66                 | 0.62        | 0.69 | 0.65        | 0.61        | 0.63 | 0.60      | 0.58                                  | 0.61 | 0.59                                  | 0.57 |  |
|                                                                                                                                                                     | 4                              | 0.66                    | 0.61                 | 0.57        | 0.65 | 0.60        | 0.56        | 0.58 | 0.55      | 0.53                                  | 0.57 | 0.54                                  | 0.51 |  |
|                                                                                                                                                                     | 5                              | 0.63                    | 0.56                 | 0.52        | 0.61 | 0.56        | 0.52        | 0.55 | 0.51      | 0.48                                  | 0.53 | 0.50                                  | 0.47 |  |
|                                                                                                                                                                     | 6                              | 0.59                    | 0.53                 | 0.48        | 0.58 | 0.52        | 0.48        | 0.51 | 0.47      | 0.45                                  | 0.50 | 0.47                                  | 0.44 |  |
|                                                                                                                                                                     | 7                              | 0.56                    | 0.49                 | 0.45        | 0.55 | 0.49        | 0.44        | 0.48 | 0.44      | 0.41                                  | 0.47 | 0.43                                  | 0.40 |  |
|                                                                                                                                                                     | 8                              | 0.53                    | 0.46                 | 0.41        | 0.52 | 0.45        | 0.41        | 0.45 | 0.41      | 0.38                                  | 0.44 | 0.40                                  | 0.37 |  |
|                                                                                                                                                                     | 9                              | 0.50                    | 0.43                 | 0.39        | 0.49 | 0.43        | 0.38        | 0.42 | 0.38      | 0.35                                  | 0.41 | 0.38                                  | 0.35 |  |
|                                                                                                                                                                     | 10                             | 0.47                    | 0.40                 | 0.36        | 0.47 | 0.40        | 0.36        | 0.39 | 0.36      | 0.33                                  | 0.39 | 0.35                                  | 0.33 |  |
| <div>7</div> <div></div> <div>8" Open reflector downlight (32W CFL)</div>          | EFF = 64.9%                    |                         |                      | % DN = 100% |      |             | % UP = 0%   |      |           | Lamp = CF6/32<br>SC (along, across)   |      |                                       |      |  |
|                                                                                                                                                                     | 0                              | 0.77                    | 0.77                 | 0.77        | 0.75 | 0.75        | 0.75        | 0.72 | 0.72      | 0.72                                  | 0.69 | 0.69                                  | 0.66 |  |
|                                                                                                                                                                     | 1                              | 0.73                    | 0.72                 | 0.70        | 0.72 | 0.70        | 0.69        | 0.67 | 0.66      | 0.65                                  | 0.65 | 0.64                                  | 0.62 |  |
|                                                                                                                                                                     | 2                              | 0.69                    | 0.66                 | 0.63        | 0.68 | 0.65        | 0.62        | 0.63 | 0.61      | 0.59                                  | 0.61 | 0.59                                  | 0.56 |  |
|                                                                                                                                                                     | 3                              | 0.66                    | 0.61                 | 0.58        | 0.64 | 0.60        | 0.57        | 0.59 | 0.56      | 0.54                                  | 0.57 | 0.55                                  | 0.52 |  |
|                                                                                                                                                                     | 4                              | 0.62                    | 0.57                 | 0.53        | 0.61 | 0.56        | 0.52        | 0.55 | 0.51      | 0.49                                  | 0.53 | 0.51                                  | 0.48 |  |
|                                                                                                                                                                     | 5                              | 0.58                    | 0.53                 | 0.49        | 0.57 | 0.52        | 0.48        | 0.51 | 0.48      | 0.45                                  | 0.50 | 0.47                                  | 0.44 |  |
|                                                                                                                                                                     | 6                              | 0.55                    | 0.49                 | 0.45        | 0.54 | 0.48        | 0.45        | 0.47 | 0.44      | 0.41                                  | 0.46 | 0.43                                  | 0.40 |  |
|                                                                                                                                                                     | 7                              | 0.52                    | 0.46                 | 0.41        | 0.51 | 0.45        | 0.41        | 0.44 | 0.41      | 0.38                                  | 0.44 | 0.40                                  | 0.37 |  |
|                                                                                                                                                                     | 8                              | 0.49                    | 0.43                 | 0.38        | 0.48 | 0.42        | 0.38        | 0.42 | 0.38      | 0.35                                  | 0.41 | 0.38                                  | 0.35 |  |
|                                                                                                                                                                     | 9                              | 0.47                    | 0.40                 | 0.36        | 0.46 | 0.40        | 0.36        | 0.39 | 0.35      | 0.33                                  | 0.38 | 0.35                                  | 0.33 |  |
| 10                                                                                                                                                                  | 0.44                           | 0.37                    | 0.33                 | 0.44        | 0.37 | 0.33        | 0.37        | 0.33 | 0.31      | 0.36                                  | 0.33 | 0.31                                  |      |  |
| <div>8</div> <div></div> <div>8" Open reflector downlight (2-26W CFL)</div>      | EFF = 61.6%                    |                         |                      | % DN = 100% |      |             | % UP = 0%   |      |           | Lamp = (2) CFQ2<br>SC (along, across) |      |                                       |      |  |
|                                                                                                                                                                     | 0                              | 0.73                    | 0.73                 | 0.73        | 0.72 | 0.72        | 0.72        | 0.68 | 0.68      | 0.68                                  | 0.66 | 0.66                                  | 0.63 |  |
|                                                                                                                                                                     | 1                              | 0.69                    | 0.67                 | 0.66        | 0.68 | 0.66        | 0.64        | 0.63 | 0.62      | 0.61                                  | 0.61 | 0.60                                  | 0.58 |  |
|                                                                                                                                                                     | 2                              | 0.65                    | 0.61                 | 0.59        | 0.64 | 0.60        | 0.58        | 0.58 | 0.56      | 0.54                                  | 0.56 | 0.55                                  | 0.53 |  |
|                                                                                                                                                                     | 3                              | 0.61                    | 0.56                 | 0.52        | 0.59 | 0.55        | 0.52        | 0.53 | 0.51      | 0.48                                  | 0.52 | 0.49                                  | 0.46 |  |
|                                                                                                                                                                     | 4                              | 0.57                    | 0.51                 | 0.47        | 0.56 | 0.50        | 0.47        | 0.49 | 0.46      | 0.43                                  | 0.48 | 0.45                                  | 0.42 |  |
|                                                                                                                                                                     | 5                              | 0.53                    | 0.47                 | 0.42        | 0.52 | 0.46        | 0.42        | 0.45 | 0.41      | 0.39                                  | 0.44 | 0.41                                  | 0.38 |  |
|                                                                                                                                                                     | 6                              | 0.50                    | 0.43                 | 0.38        | 0.48 | 0.42        | 0.38        | 0.41 | 0.38      | 0.35                                  | 0.40 | 0.37                                  | 0.34 |  |
|                                                                                                                                                                     | 7                              | 0.46                    | 0.39                 | 0.35        | 0.45 | 0.39        | 0.35        | 0.38 | 0.34      | 0.31                                  | 0.37 | 0.34                                  | 0.31 |  |
|                                                                                                                                                                     | 8                              | 0.43                    | 0.36                 | 0.32        | 0.42 | 0.36        | 0.32        | 0.35 | 0.31      | 0.29                                  | 0.34 | 0.31                                  | 0.28 |  |
|                                                                                                                                                                     | 9                              | 0.41                    | 0.33                 | 0.29        | 0.40 | 0.33        | 0.29        | 0.33 | 0.29      | 0.26                                  | 0.32 | 0.28                                  | 0.25 |  |
| 10                                                                                                                                                                  | 0.38                           | 0.31                    | 0.27                 | 0.37        | 0.31 | 0.27        | 0.30        | 0.26 | 0.24      | 0.30                                  | 0.26 | 0.23                                  |      |  |
| <div>9</div> <div></div> <div>8" Round with cross baffles</div>                  | EFF = 40.2%                    |                         |                      | % DN = 100  |      |             | % UP = 0    |      |           | Lamp = (2) CFQ2<br>SC (along, across) |      |                                       |      |  |
|                                                                                                                                                                     | 0                              | 0.47                    | 0.47                 | 0.47        | 0.46 | 0.46        | 0.46        | 0.44 | 0.44      | 0.44                                  | 0.42 | 0.42                                  | 0.40 |  |
|                                                                                                                                                                     | 1                              | 0.45                    | 0.44                 | 0.43        | 0.44 | 0.43        | 0.42        | 0.41 | 0.41      | 0.40                                  | 0.40 | 0.39                                  | 0.38 |  |
|                                                                                                                                                                     | 2                              | 0.43                    | 0.41                 | 0.39        | 0.42 | 0.40        | 0.38        | 0.39 | 0.37      | 0.36                                  | 0.37 | 0.36                                  | 0.35 |  |
|                                                                                                                                                                     | 3                              | 0.40                    | 0.37                 | 0.35        | 0.39 | 0.37        | 0.35        | 0.36 | 0.34      | 0.33                                  | 0.35 | 0.33                                  | 0.31 |  |
|                                                                                                                                                                     | 4                              | 0.38                    | 0.35                 | 0.32        | 0.37 | 0.34        | 0.32        | 0.33 | 0.31      | 0.30                                  | 0.32 | 0.31                                  | 0.29 |  |
|                                                                                                                                                                     | 5                              | 0.36                    | 0.32                 | 0.29        | 0.35 | 0.32        | 0.29        | 0.31 | 0.29      | 0.27                                  | 0.30 | 0.28                                  | 0.26 |  |
|                                                                                                                                                                     | 6                              | 0.34                    | 0.30                 | 0.27        | 0.33 | 0.29        | 0.27        | 0.29 | 0.27      | 0.25                                  | 0.28 | 0.26                                  | 0.24 |  |
|                                                                                                                                                                     | 7                              | 0.32                    | 0.28                 | 0.25        | 0.31 | 0.27        | 0.25        | 0.27 | 0.25      | 0.23                                  | 0.26 | 0.24                                  | 0.22 |  |
|                                                                                                                                                                     | 8                              | 0.30                    | 0.26                 | 0.23        | 0.29 | 0.25        | 0.23        | 0.25 | 0.23      | 0.21                                  | 0.25 | 0.23                                  | 0.21 |  |
|                                                                                                                                                                     | 9                              | 0.28                    | 0.24                 | 0.21        | 0.28 | 0.24        | 0.21        | 0.23 | 0.21      | 0.20                                  | 0.23 | 0.21                                  | 0.19 |  |
| 10                                                                                                                                                                  | 0.27                           | 0.22                    | 0.20                 | 0.26        | 0.22 | 0.20        | 0.22        | 0.20 | 0.18      | 0.22                                  | 0.20 | 0.18                                  |      |  |
| <div>10</div> <div></div> <div>8" Round with cross baffles</div>                 | EFF = 63.8%                    |                         |                      | % DN = 78.4 |      |             | % UP = 21.6 |      |           | Lamp = M100/C/1<br>SC (along, across) |      |                                       |      |  |
|                                                                                                                                                                     | 0                              | 0.76                    | 0.76                 | 0.76        | 0.74 | 0.74        | 0.74        | 0.71 | 0.71      | 0.71                                  | 0.68 | 0.68                                  | 0.66 |  |
|                                                                                                                                                                     | 1                              | 0.72                    | 0.70                 | 0.68        | 0.70 | 0.69        | 0.67        | 0.66 | 0.65      | 0.64                                  | 0.64 | 0.63                                  | 0.61 |  |
|                                                                                                                                                                     | 2                              | 0.68                    | 0.64                 | 0.62        | 0.66 | 0.63        | 0.61        | 0.61 | 0.59      | 0.57                                  | 0.59 | 0.57                                  | 0.55 |  |
|                                                                                                                                                                     | 3                              | 0.64                    | 0.59                 | 0.56        | 0.63 | 0.58        | 0.55        | 0.57 | 0.54      | 0.52                                  | 0.55 | 0.53                                  | 0.51 |  |
|                                                                                                                                                                     | 4                              | 0.60                    | 0.55                 | 0.51        | 0.59 | 0.54        | 0.50        | 0.52 | 0.49      | 0.47                                  | 0.51 | 0.48                                  | 0.46 |  |
|                                                                                                                                                                     | 5                              | 0.57                    | 0.51                 | 0.46        | 0.55 | 0.50        | 0.46        | 0.49 | 0.45      | 0.43                                  | 0.48 | 0.45                                  | 0.43 |  |
|                                                                                                                                                                     | 6                              | 0.53                    | 0.47                 | 0.43        | 0.52 | 0.46        | 0.42        | 0.45 | 0.42      | 0.39                                  | 0.44 | 0.41                                  | 0.39 |  |
|                                                                                                                                                                     | 7                              | 0.50                    | 0.43                 | 0.39        | 0.49 | 0.43        | 0.39        | 0.43 | 0.39      | 0.36                                  | 0.41 | 0.38                                  | 0.35 |  |
|                                                                                                                                                                     | 8                              | 0.47                    | 0.40                 | 0.36        | 0.46 | 0.40        | 0.36        | 0.40 | 0.36      | 0.33                                  | 0.38 | 0.35                                  | 0.33 |  |
|                                                                                                                                                                     | 9                              | 0.44                    | 0.37                 | 0.33        | 0.44 | 0.37        | 0.33        | 0.37 | 0.33      | 0.31                                  | 0.36 | 0.33                                  | 0.31 |  |
| 10                                                                                                                                                                  | 0.41                           | 0.34                    | 0.30                 | 0.41        | 0.34 | 0.30        | 0.34        | 0.30 | 0.28      | 0.33                                  | 0.30 | 0.28                                  |      |  |



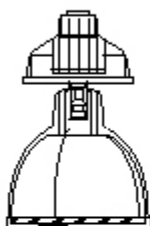
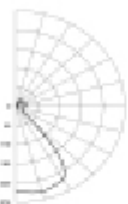
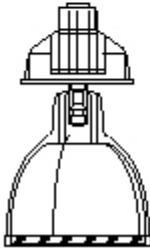
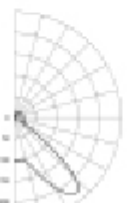
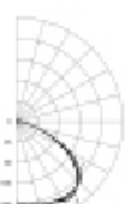
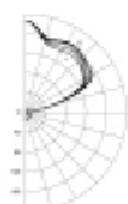
|                        |    |      |      |      |      |      |      |      |      |      |      |      |     |
|------------------------|----|------|------|------|------|------|------|------|------|------|------|------|-----|
|                        |    | 0.00 | 0.10 | 0.20 | 0.30 | 0.40 | 0.50 | 0.60 | 0.70 | 0.80 | 0.90 | 1.00 |     |
| Metal halide downlight | 8  | 0.47 | 0.41 | 0.36 | 0.46 | 0.40 | 0.36 | 0.39 | 0.36 | 0.33 | 0.39 | 0.35 | 0.3 |
|                        | 9  | 0.45 | 0.38 | 0.34 | 0.44 | 0.37 | 0.33 | 0.37 | 0.33 | 0.31 | 0.36 | 0.33 | 0.3 |
|                        | 10 | 0.42 | 0.35 | 0.31 | 0.42 | 0.35 | 0.31 | 0.35 | 0.31 | 0.28 | 0.34 | 0.31 | 0.2 |

Figure 9-28 *Continued*

| Typical Luminaire                      | Typical Intensity Distribution                                                      | $\rho_{cc} \rightarrow$ |             |      | 80          |              |      | 70           |             |      | 50           |                                       |      | 30                                    |      |      |
|----------------------------------------|-------------------------------------------------------------------------------------|-------------------------|-------------|------|-------------|--------------|------|--------------|-------------|------|--------------|---------------------------------------|------|---------------------------------------|------|------|
|                                        |                                                                                     | $\rho_w \rightarrow$    |             |      | 70          | 50           | 30   | 70           | 50          | 30   | 50           | 30                                    | 10   | 50                                    | 30   | 10   |
|                                        |                                                                                     | RCR ↓                   |             |      | EFF = 55.9% |              |      | % DN = 76.2% |             |      | % UP = 23.8% |                                       |      | Lamp = 22 & 32V<br>SC (along, across) |      |      |
| 11                                     |    | 0                       | 0.63        | 0.63 | 0.63        | 0.60         | 0.60 | 0.60         | 0.55        | 0.55 | 0.55         | 0.50                                  | 0.50 | 0.50                                  | 0.50 | 0.50 |
|                                        |                                                                                     | 1                       | 0.57        | 0.54 | 0.51        | 0.54         | 0.51 | 0.48         | 0.46        | 0.44 | 0.42         | 0.42                                  | 0.40 | 0.40                                  | 0.40 | 0.38 |
|                                        |                                                                                     | 2                       | 0.51        | 0.46 | 0.42        | 0.48         | 0.44 | 0.40         | 0.40        | 0.37 | 0.34         | 0.36                                  | 0.33 | 0.33                                  | 0.31 | 0.28 |
|                                        |                                                                                     | 3                       | 0.46        | 0.40 | 0.35        | 0.44         | 0.38 | 0.34         | 0.35        | 0.31 | 0.28         | 0.31                                  | 0.28 | 0.28                                  | 0.24 | 0.21 |
|                                        |                                                                                     | 4                       | 0.42        | 0.35 | 0.30        | 0.40         | 0.34 | 0.29         | 0.31        | 0.27 | 0.24         | 0.28                                  | 0.24 | 0.24                                  | 0.22 | 0.19 |
|                                        |                                                                                     | 5                       | 0.39        | 0.31 | 0.26        | 0.37         | 0.30 | 0.25         | 0.27        | 0.23 | 0.20         | 0.25                                  | 0.21 | 0.21                                  | 0.18 | 0.15 |
|                                        |                                                                                     | 6                       | 0.36        | 0.28 | 0.23        | 0.34         | 0.27 | 0.22         | 0.24        | 0.20 | 0.18         | 0.22                                  | 0.19 | 0.19                                  | 0.16 | 0.13 |
|                                        |                                                                                     | 7                       | 0.33        | 0.25 | 0.20        | 0.31         | 0.24 | 0.20         | 0.22        | 0.18 | 0.15         | 0.20                                  | 0.17 | 0.17                                  | 0.14 | 0.11 |
|                                        |                                                                                     | 8                       | 0.31        | 0.23 | 0.18        | 0.29         | 0.22 | 0.18         | 0.20        | 0.16 | 0.14         | 0.18                                  | 0.15 | 0.15                                  | 0.12 | 0.09 |
|                                        |                                                                                     | 9                       | 0.28        | 0.21 | 0.16        | 0.27         | 0.20 | 0.16         | 0.18        | 0.15 | 0.12         | 0.17                                  | 0.14 | 0.14                                  | 0.11 | 0.08 |
|                                        |                                                                                     | 10                      | 0.27        | 0.19 | 0.15        | 0.25         | 0.19 | 0.14         | 0.17        | 0.13 | 0.11         | 0.16                                  | 0.13 | 0.13                                  | 0.10 | 0.07 |
| CFL surface-mounted disk               |                                                                                     |                         |             |      |             |              |      |              |             |      |              |                                       |      |                                       |      |      |
| 12                                     |   |                         | EFF = 87.5% |      |             | % DN = 85.9% |      |              | % UP = 1.6% |      |              | Lamp = M400/C/I<br>SC (along, across) |      |                                       |      |      |
|                                        |                                                                                     | 0                       | 1.04        | 1.04 | 1.04        | 1.01         | 1.01 | 1.01         | 0.96        | 0.96 | 0.96         | 0.92                                  | 0.92 | 0.92                                  | 0.92 | 0.92 |
|                                        |                                                                                     | 1                       | 0.98        | 0.95 | 0.93        | 0.96         | 0.93 | 0.91         | 0.89        | 0.87 | 0.86         | 0.86                                  | 0.84 | 0.84                                  | 0.83 | 0.81 |
|                                        |                                                                                     | 2                       | 0.92        | 0.87 | 0.83        | 0.90         | 0.85 | 0.82         | 0.82        | 0.79 | 0.76         | 0.79                                  | 0.77 | 0.77                                  | 0.74 | 0.71 |
|                                        |                                                                                     | 3                       | 0.86        | 0.80 | 0.75        | 0.84         | 0.78 | 0.74         | 0.76        | 0.72 | 0.69         | 0.73                                  | 0.70 | 0.70                                  | 0.67 | 0.64 |
|                                        |                                                                                     | 4                       | 0.81        | 0.73 | 0.68        | 0.79         | 0.72 | 0.67         | 0.70        | 0.66 | 0.62         | 0.68                                  | 0.64 | 0.64                                  | 0.61 | 0.58 |
|                                        |                                                                                     | 5                       | 0.76        | 0.68 | 0.62        | 0.74         | 0.67 | 0.61         | 0.65        | 0.60 | 0.56         | 0.63                                  | 0.59 | 0.59                                  | 0.56 | 0.53 |
|                                        |                                                                                     | 6                       | 0.72        | 0.63 | 0.57        | 0.70         | 0.62 | 0.56         | 0.60        | 0.55 | 0.52         | 0.59                                  | 0.54 | 0.54                                  | 0.51 | 0.48 |
|                                        |                                                                                     | 7                       | 0.67        | 0.58 | 0.52        | 0.66         | 0.58 | 0.52         | 0.56        | 0.51 | 0.47         | 0.55                                  | 0.50 | 0.50                                  | 0.47 | 0.44 |
|                                        |                                                                                     | 8                       | 0.64        | 0.54 | 0.48        | 0.62         | 0.54 | 0.48         | 0.53        | 0.47 | 0.44         | 0.51                                  | 0.47 | 0.47                                  | 0.44 | 0.41 |
|                                        |                                                                                     | 9                       | 0.60        | 0.51 | 0.45        | 0.59         | 0.50 | 0.45         | 0.49        | 0.44 | 0.41         | 0.48                                  | 0.44 | 0.44                                  | 0.41 | 0.38 |
|                                        |                                                                                     | 10                      | 0.57        | 0.48 | 0.42        | 0.56         | 0.47 | 0.42         | 0.46        | 0.41 | 0.38         | 0.45                                  | 0.41 | 0.41                                  | 0.38 | 0.35 |
| High bay, open metal reflector, narrow |                                                                                     |                         |             |      |             |              |      |              |             |      |              |                                       |      |                                       |      |      |
| 13                                     |  |                         | EFF = 83.9% |      |             | % DN = 95.2% |      |              | % UP = 4.8% |      |              | Lamp = M400/C/I<br>SC (along, across) |      |                                       |      |      |
|                                        |                                                                                     | 0                       | 0.99        | 0.99 | 0.99        | 0.96         | 0.96 | 0.96         | 0.91        | 0.91 | 0.91         | 0.86                                  | 0.86 | 0.86                                  | 0.86 | 0.86 |
|                                        |                                                                                     | 1                       | 0.93        | 0.90 | 0.87        | 0.90         | 0.88 | 0.85         | 0.83        | 0.81 | 0.80         | 0.80                                  | 0.78 | 0.78                                  | 0.77 | 0.75 |
|                                        |                                                                                     | 2                       | 0.86        | 0.81 | 0.77        | 0.84         | 0.79 | 0.75         | 0.76        | 0.73 | 0.70         | 0.73                                  | 0.70 | 0.70                                  | 0.68 | 0.65 |
|                                        |                                                                                     | 3                       | 0.80        | 0.73 | 0.68        | 0.78         | 0.72 | 0.67         | 0.65        | 0.65 | 0.61         | 0.66                                  | 0.63 | 0.63                                  | 0.61 | 0.58 |
|                                        |                                                                                     | 4                       | 0.75        | 0.67 | 0.61        | 0.73         | 0.65 | 0.60         | 0.63        | 0.58 | 0.54         | 0.61                                  | 0.57 | 0.57                                  | 0.54 | 0.51 |
|                                        |                                                                                     | 5                       | 0.70        | 0.61 | 0.54        | 0.68         | 0.59 | 0.54         | 0.57        | 0.52 | 0.48         | 0.55                                  | 0.51 | 0.51                                  | 0.48 | 0.45 |
|                                        |                                                                                     | 6                       | 0.65        | 0.55 | 0.49        | 0.63         | 0.54 | 0.48         | 0.53        | 0.47 | 0.43         | 0.51                                  | 0.46 | 0.46                                  | 0.43 | 0.40 |
|                                        |                                                                                     | 7                       | 0.60        | 0.51 | 0.44        | 0.59         | 0.50 | 0.44         | 0.48        | 0.43 | 0.39         | 0.47                                  | 0.42 | 0.42                                  | 0.39 | 0.36 |
|                                        |                                                                                     | 8                       | 0.56        | 0.47 | 0.40        | 0.55         | 0.46 | 0.40         | 0.44        | 0.39 | 0.35         | 0.43                                  | 0.38 | 0.38                                  | 0.35 | 0.32 |
|                                        |                                                                                     | 9                       | 0.53        | 0.43 | 0.37        | 0.52         | 0.42 | 0.36         | 0.41        | 0.36 | 0.32         | 0.40                                  | 0.35 | 0.35                                  | 0.32 | 0.29 |
|                                        |                                                                                     | 10                      | 0.50        | 0.40 | 0.34        | 0.48         | 0.39 | 0.33         | 0.38        | 0.33 | 0.29         | 0.37                                  | 0.32 | 0.32                                  | 0.29 | 0.26 |
| High bay, open metal reflector, medium |                                                                                     |                         |             |      |             |              |      |              |             |      |              |                                       |      |                                       |      |      |
| 14                                     |  |                         | EFF = 83.8% |      |             | % DN = 97    |      |              | % UP = 3    |      |              | Lamp = M400/C/I<br>SC (along, across) |      |                                       |      |      |
|                                        |                                                                                     | 0                       | 0.99        | 0.99 | 0.99        | 0.97         | 0.97 | 0.97         | 0.92        | 0.92 | 0.92         | 0.87                                  | 0.87 | 0.87                                  | 0.87 | 0.87 |
|                                        |                                                                                     | 1                       | 0.92        | 0.89 | 0.86        | 0.90         | 0.87 | 0.84         | 0.83        | 0.81 | 0.79         | 0.80                                  | 0.78 | 0.78                                  | 0.76 | 0.73 |
|                                        |                                                                                     | 2                       | 0.85        | 0.80 | 0.75        | 0.83         | 0.78 | 0.73         | 0.75        | 0.71 | 0.68         | 0.72                                  | 0.69 | 0.69                                  | 0.66 | 0.63 |
|                                        |                                                                                     | 3                       | 0.79        | 0.71 | 0.65        | 0.76         | 0.70 | 0.64         | 0.67        | 0.62 | 0.58         | 0.64                                  | 0.60 | 0.60                                  | 0.57 | 0.54 |
|                                        |                                                                                     | 4                       | 0.72        | 0.63 | 0.57        | 0.70         | 0.62 | 0.56         | 0.60        | 0.55 | 0.51         | 0.58                                  | 0.53 | 0.53                                  | 0.50 | 0.47 |
|                                        |                                                                                     | 5                       | 0.67        | 0.57 | 0.50        | 0.65         | 0.56 | 0.50         | 0.54        | 0.48 | 0.44         | 0.52                                  | 0.47 | 0.47                                  | 0.44 | 0.41 |
|                                        |                                                                                     | 6                       | 0.62        | 0.51 | 0.44        | 0.60         | 0.50 | 0.44         | 0.49        | 0.43 | 0.39         | 0.47                                  | 0.42 | 0.42                                  | 0.39 | 0.36 |
|                                        |                                                                                     | 7                       | 0.57        | 0.46 | 0.40        | 0.56         | 0.46 | 0.39         | 0.44        | 0.38 | 0.34         | 0.43                                  | 0.38 | 0.38                                  | 0.35 | 0.32 |
|                                        |                                                                                     | 8                       | 0.53        | 0.42 | 0.35        | 0.52         | 0.42 | 0.35         | 0.40        | 0.34 | 0.30         | 0.39                                  | 0.34 | 0.34                                  | 0.31 | 0.28 |
|                                        |                                                                                     | 9                       | 0.49        | 0.39 | 0.32        | 0.48         | 0.38 | 0.32         | 0.37        | 0.31 | 0.27         | 0.36                                  | 0.31 | 0.31                                  | 0.28 | 0.25 |
|                                        |                                                                                     | 10                      | 0.46        | 0.35 | 0.29        | 0.45         | 0.35 | 0.29         | 0.34        | 0.28 | 0.24         | 0.33                                  | 0.28 | 0.28                                  | 0.25 | 0.22 |
| High bay, open metal reflector, wide   |                                                                                     |                         |             |      |             |              |      |              |             |      |              |                                       |      |                                       |      |      |
| 15                                     |  |                         | EFF = 61.4% |      |             | % DN = 80.6  |      |              | % UP = 19.4 |      |              | Lamp = M400/C/I<br>SC (along, across) |      |                                       |      |      |
|                                        |                                                                                     | 0                       | 0.70        | 0.70 | 0.70        | 0.67         | 0.67 | 0.67         | 0.62        | 0.62 | 0.62         | 0.56                                  | 0.56 | 0.56                                  | 0.56 | 0.56 |
|                                        |                                                                                     | 1                       | 0.65        | 0.62 | 0.60        | 0.62         | 0.59 | 0.57         | 0.55        | 0.53 | 0.52         | 0.50                                  | 0.49 | 0.49                                  | 0.48 | 0.46 |
|                                        |                                                                                     | 2                       | 0.60        | 0.55 | 0.52        | 0.57         | 0.53 | 0.50         | 0.49        | 0.47 | 0.45         | 0.46                                  | 0.44 | 0.44                                  | 0.42 | 0.40 |
|                                        |                                                                                     | 3                       | 0.56        | 0.50 | 0.46        | 0.53         | 0.48 | 0.44         | 0.45        | 0.42 | 0.39         | 0.42                                  | 0.39 | 0.39                                  | 0.37 | 0.34 |

|                                                                                                                                 |                                                                                   |    |      |      |      |      |      |      |      |      |      |      |      |      |
|---------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|----|------|------|------|------|------|------|------|------|------|------|------|------|
| <br>High bay, open prismatic reflector, narrow |  | 4  | 0.52 | 0.45 | 0.41 | 0.49 | 0.44 | 0.40 | 0.41 | 0.38 | 0.35 | 0.38 | 0.35 | 0.33 |
|                                                                                                                                 |                                                                                   | 5  | 0.48 | 0.41 | 0.37 | 0.46 | 0.40 | 0.36 | 0.38 | 0.34 | 0.31 | 0.35 | 0.32 | 0.30 |
|                                                                                                                                 |                                                                                   | 6  | 0.45 | 0.38 | 0.33 | 0.43 | 0.37 | 0.33 | 0.35 | 0.31 | 0.28 | 0.33 | 0.30 | 0.27 |
|                                                                                                                                 |                                                                                   | 7  | 0.42 | 0.35 | 0.30 | 0.40 | 0.34 | 0.30 | 0.32 | 0.28 | 0.26 | 0.30 | 0.27 | 0.24 |
|                                                                                                                                 |                                                                                   | 8  | 0.40 | 0.32 | 0.28 | 0.38 | 0.31 | 0.27 | 0.30 | 0.26 | 0.24 | 0.28 | 0.25 | 0.23 |
|                                                                                                                                 |                                                                                   | 9  | 0.37 | 0.30 | 0.26 | 0.36 | 0.29 | 0.25 | 0.28 | 0.24 | 0.22 | 0.26 | 0.23 | 0.21 |
|                                                                                                                                 |                                                                                   | 10 | 0.35 | 0.28 | 0.24 | 0.34 | 0.27 | 0.23 | 0.26 | 0.22 | 0.20 | 0.25 | 0.22 | 0.19 |

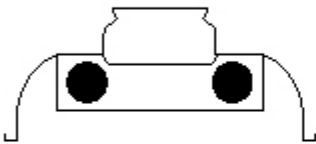
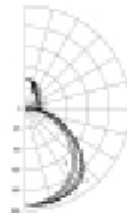
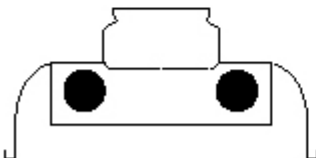
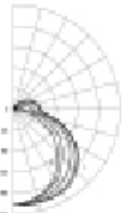
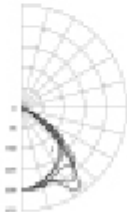
Figure 9-28 *Continued*

| Typical Luminaire                          | Typical Intensity Distribution                                                      | $\rho_{cc} \rightarrow$                                                             | 80          |      |      | 70           |      |      | 50           |      |      | 30                                     |      |      |      |
|--------------------------------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-------------|------|------|--------------|------|------|--------------|------|------|----------------------------------------|------|------|------|
|                                            |                                                                                     | $\rho_w \rightarrow$                                                                | 70          | 50   | 30   | 70           | 50   | 30   | 50           | 30   | 10   | 50                                     | 30   | 10   |      |
|                                            |                                                                                     | RCR<br>↓                                                                            | EFF = 59%   |      |      | % DN = 77.9% |      |      | % UP = 22.1% |      |      | Lamp = M400/C/L<br>SC (along, across,  |      |      |      |
| 16                                         |    |    | 0           | 0.67 | 0.67 | 0.67         | 0.64 | 0.64 | 0.64         | 0.58 | 0.58 | 0.58                                   | 0.53 | 0.53 | 0.53 |
|                                            |                                                                                     |                                                                                     | 1           | 0.62 | 0.59 | 0.57         | 0.59 | 0.57 | 0.55         | 0.52 | 0.50 | 0.49                                   | 0.48 | 0.46 | 0.45 |
|                                            |                                                                                     |                                                                                     | 2           | 0.57 | 0.53 | 0.50         | 0.55 | 0.51 | 0.48         | 0.47 | 0.45 | 0.43                                   | 0.43 | 0.41 | 0.40 |
|                                            |                                                                                     |                                                                                     | 3           | 0.53 | 0.48 | 0.44         | 0.51 | 0.46 | 0.43         | 0.43 | 0.40 | 0.37                                   | 0.40 | 0.37 | 0.35 |
|                                            |                                                                                     |                                                                                     | 4           | 0.50 | 0.44 | 0.39         | 0.47 | 0.42 | 0.38         | 0.39 | 0.36 | 0.33                                   | 0.36 | 0.34 | 0.32 |
|                                            |                                                                                     |                                                                                     | 5           | 0.46 | 0.40 | 0.35         | 0.44 | 0.38 | 0.34         | 0.36 | 0.33 | 0.30                                   | 0.33 | 0.31 | 0.28 |
|                                            |                                                                                     |                                                                                     | 6           | 0.43 | 0.37 | 0.32         | 0.41 | 0.35 | 0.31         | 0.33 | 0.30 | 0.27                                   | 0.31 | 0.28 | 0.26 |
|                                            |                                                                                     |                                                                                     | 7           | 0.40 | 0.34 | 0.29         | 0.39 | 0.33 | 0.28         | 0.31 | 0.27 | 0.25                                   | 0.29 | 0.26 | 0.24 |
|                                            |                                                                                     |                                                                                     | 8           | 0.38 | 0.31 | 0.27         | 0.36 | 0.30 | 0.26         | 0.28 | 0.25 | 0.22                                   | 0.27 | 0.24 | 0.22 |
|                                            |                                                                                     |                                                                                     | 9           | 0.36 | 0.29 | 0.24         | 0.34 | 0.28 | 0.24         | 0.26 | 0.23 | 0.21                                   | 0.25 | 0.22 | 0.20 |
|                                            |                                                                                     |                                                                                     | 10          | 0.33 | 0.27 | 0.23         | 0.32 | 0.26 | 0.22         | 0.24 | 0.21 | 0.19                                   | 0.23 | 0.20 | 0.18 |
| High bay, open prismatic reflector, medium |                                                                                     |                                                                                     | EFF = 61.5% |      |      | % DN = 83.7% |      |      | % UP = 16.3% |      |      | Lamp = M400/C/L<br>SC (along, across,  |      |      |      |
| 17                                         |   |   | 0           | 0.71 | 0.71 | 0.71         | 0.68 | 0.68 | 0.68         | 0.63 | 0.63 | 0.63                                   | 0.58 | 0.58 | 0.58 |
|                                            |                                                                                     |                                                                                     | 1           | 0.65 | 0.62 | 0.59         | 0.62 | 0.59 | 0.57         | 0.55 | 0.53 | 0.52                                   | 0.51 | 0.50 | 0.48 |
|                                            |                                                                                     |                                                                                     | 2           | 0.59 | 0.55 | 0.51         | 0.57 | 0.53 | 0.49         | 0.49 | 0.46 | 0.43                                   | 0.45 | 0.43 | 0.41 |
|                                            |                                                                                     |                                                                                     | 3           | 0.54 | 0.48 | 0.44         | 0.52 | 0.47 | 0.42         | 0.43 | 0.40 | 0.37                                   | 0.40 | 0.38 | 0.35 |
|                                            |                                                                                     |                                                                                     | 4           | 0.50 | 0.43 | 0.38         | 0.48 | 0.42 | 0.37         | 0.39 | 0.35 | 0.32                                   | 0.36 | 0.33 | 0.30 |
|                                            |                                                                                     |                                                                                     | 5           | 0.46 | 0.38 | 0.33         | 0.44 | 0.37 | 0.32         | 0.35 | 0.31 | 0.27                                   | 0.32 | 0.29 | 0.26 |
|                                            |                                                                                     |                                                                                     | 6           | 0.42 | 0.34 | 0.29         | 0.40 | 0.33 | 0.28         | 0.31 | 0.27 | 0.24                                   | 0.29 | 0.26 | 0.23 |
|                                            |                                                                                     |                                                                                     | 7           | 0.39 | 0.31 | 0.26         | 0.37 | 0.30 | 0.25         | 0.28 | 0.24 | 0.21                                   | 0.27 | 0.23 | 0.20 |
|                                            |                                                                                     |                                                                                     | 8           | 0.36 | 0.28 | 0.23         | 0.35 | 0.27 | 0.22         | 0.26 | 0.21 | 0.18                                   | 0.24 | 0.20 | 0.18 |
|                                            |                                                                                     |                                                                                     | 9           | 0.34 | 0.25 | 0.21         | 0.32 | 0.25 | 0.20         | 0.23 | 0.19 | 0.16                                   | 0.22 | 0.18 | 0.16 |
|                                            |                                                                                     |                                                                                     | 10          | 0.31 | 0.23 | 0.19         | 0.30 | 0.23 | 0.18         | 0.21 | 0.17 | 0.15                                   | 0.20 | 0.17 | 0.14 |
| High bay, open prismatic reflector, wide   |                                                                                     |                                                                                     | EFF = 72.5% |      |      | % DN = 97.8% |      |      | % UP = 2.2%  |      |      | Lamp = M400/C/L<br>SC (along, across,  |      |      |      |
| 18                                         |  |  | 0           | 0.86 | 0.86 | 0.86         | 0.84 | 0.84 | 0.84         | 0.80 | 0.80 | 0.80                                   | 0.76 | 0.76 | 0.76 |
|                                            |                                                                                     |                                                                                     | 1           | 0.78 | 0.75 | 0.71         | 0.76 | 0.73 | 0.70         | 0.69 | 0.67 | 0.65                                   | 0.66 | 0.64 | 0.63 |
|                                            |                                                                                     |                                                                                     | 2           | 0.71 | 0.65 | 0.60         | 0.69 | 0.63 | 0.59         | 0.60 | 0.56 | 0.53                                   | 0.58 | 0.54 | 0.52 |
|                                            |                                                                                     |                                                                                     | 3           | 0.64 | 0.56 | 0.50         | 0.62 | 0.55 | 0.50         | 0.53 | 0.48 | 0.44                                   | 0.51 | 0.46 | 0.43 |
|                                            |                                                                                     |                                                                                     | 4           | 0.59 | 0.50 | 0.43         | 0.57 | 0.49 | 0.42         | 0.47 | 0.41 | 0.37                                   | 0.45 | 0.40 | 0.36 |
|                                            |                                                                                     |                                                                                     | 5           | 0.54 | 0.44 | 0.37         | 0.52 | 0.43 | 0.37         | 0.41 | 0.36 | 0.32                                   | 0.40 | 0.35 | 0.31 |
|                                            |                                                                                     |                                                                                     | 6           | 0.49 | 0.39 | 0.33         | 0.48 | 0.39 | 0.32         | 0.37 | 0.31 | 0.27                                   | 0.36 | 0.31 | 0.27 |
|                                            |                                                                                     |                                                                                     | 7           | 0.46 | 0.35 | 0.29         | 0.44 | 0.35 | 0.28         | 0.33 | 0.28 | 0.24                                   | 0.32 | 0.27 | 0.23 |
|                                            |                                                                                     |                                                                                     | 8           | 0.42 | 0.32 | 0.26         | 0.41 | 0.31 | 0.25         | 0.30 | 0.25 | 0.21                                   | 0.29 | 0.24 | 0.21 |
|                                            |                                                                                     |                                                                                     | 9           | 0.39 | 0.29 | 0.23         | 0.38 | 0.29 | 0.23         | 0.28 | 0.22 | 0.19                                   | 0.27 | 0.22 | 0.18 |
|                                            |                                                                                     |                                                                                     | 10          | 0.37 | 0.27 | 0.21         | 0.36 | 0.26 | 0.21         | 0.26 | 0.20 | 0.17                                   | 0.25 | 0.20 | 0.17 |
| Low bay with drop lens, narrow             |                                                                                     |                                                                                     | EFF = 75.3% |      |      | % DN = 8.1   |      |      | % UP = 91.9  |      |      | Lamp = M175/C*<br>SC (along, across,   |      |      |      |
| 19                                         |  |  | 0           | 0.73 | 0.73 | 0.73         | 0.63 | 0.63 | 0.63         | 0.45 | 0.45 | 0.45                                   | 0.29 | 0.29 | 0.29 |
|                                            |                                                                                     |                                                                                     | 1           | 0.66 | 0.63 | 0.60         | 0.57 | 0.55 | 0.52         | 0.39 | 0.38 | 0.36                                   | 0.25 | 0.24 | 0.23 |
|                                            |                                                                                     |                                                                                     | 2           | 0.60 | 0.55 | 0.51         | 0.52 | 0.48 | 0.44         | 0.34 | 0.32 | 0.30                                   | 0.21 | 0.20 | 0.19 |
|                                            |                                                                                     |                                                                                     | 3           | 0.55 | 0.48 | 0.43         | 0.47 | 0.42 | 0.37         | 0.30 | 0.27 | 0.25                                   | 0.19 | 0.17 | 0.16 |
|                                            |                                                                                     |                                                                                     | 4           | 0.50 | 0.42 | 0.37         | 0.43 | 0.37 | 0.32         | 0.26 | 0.23 | 0.21                                   | 0.17 | 0.15 | 0.13 |
|                                            |                                                                                     |                                                                                     | 5           | 0.46 | 0.37 | 0.32         | 0.39 | 0.33 | 0.28         | 0.23 | 0.20 | 0.18                                   | 0.15 | 0.13 | 0.11 |
|                                            |                                                                                     |                                                                                     | 6           | 0.42 | 0.33 | 0.28         | 0.36 | 0.29 | 0.24         | 0.21 | 0.18 | 0.15                                   | 0.13 | 0.11 | 0.10 |
|                                            |                                                                                     |                                                                                     | 7           | 0.39 | 0.30 | 0.24         | 0.33 | 0.26 | 0.21         | 0.19 | 0.16 | 0.13                                   | 0.12 | 0.10 | 0.09 |
|                                            |                                                                                     |                                                                                     | 8           | 0.36 | 0.27 | 0.21         | 0.31 | 0.23 | 0.19         | 0.17 | 0.14 | 0.12                                   | 0.11 | 0.09 | 0.07 |
|                                            |                                                                                     |                                                                                     | 9           | 0.33 | 0.24 | 0.19         | 0.28 | 0.21 | 0.17         | 0.15 | 0.12 | 0.10                                   | 0.10 | 0.08 | 0.07 |
|                                            |                                                                                     |                                                                                     | 10          | 0.31 | 0.22 | 0.17         | 0.26 | 0.19 | 0.15         | 0.14 | 0.11 | 0.09                                   | 0.09 | 0.07 | 0.06 |
| Glowing suspended bowl, MH                 |                                                                                     |                                                                                     | EFF = 81.5% |      |      | % DN = 15.3  |      |      | % UP = 84.7  |      |      | Lamp = (4) FT39*<br>SC (along, across, |      |      |      |
| 20                                         |  |  | 0           | 0.81 | 0.81 | 0.81         | 0.71 | 0.71 | 0.71         | 0.52 | 0.52 | 0.52                                   | 0.35 | 0.35 | 0.35 |

|                                                                                   |    |      |      |      |      |      |      |      |      |      |      |      |      |
|-----------------------------------------------------------------------------------|----|------|------|------|------|------|------|------|------|------|------|------|------|
|  | 0  | 0.73 | 0.69 | 0.66 | 0.64 | 0.61 | 0.58 | 0.45 | 0.43 | 0.42 | 0.30 | 0.29 | 0.28 |
|                                                                                   | 1  | 0.66 | 0.60 | 0.55 | 0.58 | 0.53 | 0.49 | 0.39 | 0.36 | 0.34 | 0.26 | 0.25 | 0.23 |
|                                                                                   | 2  | 0.60 | 0.53 | 0.47 | 0.53 | 0.46 | 0.42 | 0.34 | 0.31 | 0.29 | 0.23 | 0.21 | 0.20 |
|                                                                                   | 3  | 0.55 | 0.47 | 0.40 | 0.48 | 0.41 | 0.36 | 0.30 | 0.27 | 0.24 | 0.20 | 0.18 | 0.17 |
|                                                                                   | 4  | 0.50 | 0.41 | 0.35 | 0.44 | 0.36 | 0.31 | 0.27 | 0.23 | 0.20 | 0.18 | 0.16 | 0.14 |
|                                                                                   | 5  | 0.46 | 0.37 | 0.30 | 0.40 | 0.32 | 0.27 | 0.24 | 0.20 | 0.18 | 0.16 | 0.14 | 0.12 |
|                                                                                   | 6  | 0.42 | 0.33 | 0.27 | 0.37 | 0.29 | 0.24 | 0.22 | 0.18 | 0.15 | 0.15 | 0.12 | 0.11 |
|                                                                                   | 7  | 0.39 | 0.30 | 0.24 | 0.34 | 0.26 | 0.21 | 0.20 | 0.16 | 0.13 | 0.13 | 0.11 | 0.09 |
|                                                                                   | 8  | 0.36 | 0.27 | 0.21 | 0.32 | 0.24 | 0.19 | 0.18 | 0.14 | 0.12 | 0.12 | 0.10 | 0.08 |
|                                                                                   | 9  | 0.34 | 0.25 | 0.19 | 0.30 | 0.22 | 0.17 | 0.16 | 0.13 | 0.11 | 0.11 | 0.09 | 0.07 |
|                                                                                   | 10 |      |      |      |      |      |      |      |      |      |      |      |      |

Glowing suspended bowl, CFL

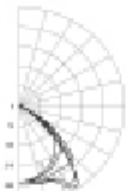
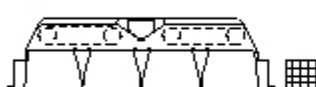
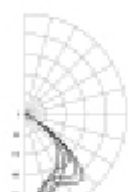
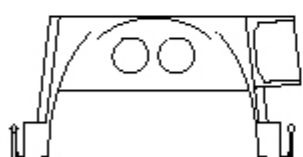
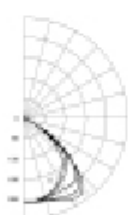
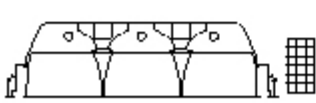
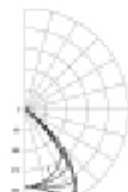
Figure 9-28 Continued

| Typical Luminaire                                                                                                                                                 | Typical Intensity Distribution                                                      | $\rho_{cc} \rightarrow$                                                                                                                 | 80                                                                                  |             |              | 70   |             |              | 50   |           |                                        | 30   |                                        |      |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-------------|--------------|------|-------------|--------------|------|-----------|----------------------------------------|------|----------------------------------------|------|
|                                                                                                                                                                   |                                                                                     | $\rho_w \rightarrow$                                                                                                                    | 70                                                                                  | 50          | 30           | 70   | 50          | 30           | 50   | 30        | 10                                     | 50   | 30                                     | 10   |
|                                                                                                                                                                   |                                                                                     | RCR<br>↓                                                                                                                                | Lamp = (2) F40T1<br>SC (along, across)                                              |             |              |      |             |              |      |           |                                        |      |                                        |      |
| <br>Industrial, white enamel reflector,<br>20% up                                |    | 0                                                                                                                                       | 1.03                                                                                | 1.03        | 1.03         | 0.98 | 0.98        | 0.98         | 0.90 | 0.90      | 0.90                                   | 0.82 | 0.82                                   | 0.82 |
|                                                                                                                                                                   |                                                                                     | 1                                                                                                                                       | 0.93                                                                                | 0.89        | 0.85         | 0.89 | 0.85        | 0.81         | 0.77 | 0.74      | 0.72                                   | 0.70 | 0.68                                   | 0.66 |
|                                                                                                                                                                   |                                                                                     | 2                                                                                                                                       | 0.84                                                                                | 0.77        | 0.71         | 0.80 | 0.74        | 0.68         | 0.67 | 0.63      | 0.59                                   | 0.61 | 0.58                                   | 0.54 |
|                                                                                                                                                                   |                                                                                     | 3                                                                                                                                       | 0.77                                                                                | 0.67        | 0.60         | 0.73 | 0.64        | 0.58         | 0.59 | 0.53      | 0.49                                   | 0.54 | 0.49                                   | 0.45 |
|                                                                                                                                                                   |                                                                                     | 4                                                                                                                                       | 0.70                                                                                | 0.59        | 0.51         | 0.66 | 0.57        | 0.50         | 0.52 | 0.46      | 0.41                                   | 0.48 | 0.43                                   | 0.39 |
|                                                                                                                                                                   |                                                                                     | 5                                                                                                                                       | 0.64                                                                                | 0.53        | 0.45         | 0.61 | 0.51        | 0.43         | 0.46 | 0.40      | 0.35                                   | 0.43 | 0.37                                   | 0.33 |
|                                                                                                                                                                   |                                                                                     | 6                                                                                                                                       | 0.59                                                                                | 0.47        | 0.39         | 0.56 | 0.45        | 0.38         | 0.42 | 0.35      | 0.31                                   | 0.38 | 0.33                                   | 0.29 |
|                                                                                                                                                                   |                                                                                     | 7                                                                                                                                       | 0.55                                                                                | 0.43        | 0.35         | 0.52 | 0.41        | 0.34         | 0.38 | 0.32      | 0.27                                   | 0.35 | 0.30                                   | 0.26 |
|                                                                                                                                                                   |                                                                                     | 8                                                                                                                                       | 0.51                                                                                | 0.39        | 0.31         | 0.48 | 0.37        | 0.30         | 0.34 | 0.28      | 0.24                                   | 0.32 | 0.27                                   | 0.23 |
|                                                                                                                                                                   |                                                                                     | 9                                                                                                                                       | 0.47                                                                                | 0.35        | 0.28         | 0.45 | 0.34        | 0.27         | 0.32 | 0.26      | 0.21                                   | 0.29 | 0.24                                   | 0.20 |
|                                                                                                                                                                   |                                                                                     | 10                                                                                                                                      | 0.44                                                                                | 0.33        | 0.26         | 0.42 | 0.31        | 0.25         | 0.29 | 0.23      | 0.19                                   | 0.27 | 0.22                                   | 0.18 |
|                                                                                                                                                                   |                                                                                     | <br>Industrial, white enamel reflector,<br>down only |  | EFF = 86.9% |              |      | % DN = 100% |              |      | % UP = 0% |                                        |      | Lamp = (2) F40T1<br>SC (along, across) |      |
| 0                                                                                                                                                                 | 1.03                                                                                |                                                                                                                                         |                                                                                     | 1.03        | 1.03         | 1.01 | 1.01        | 1.01         | 0.97 | 0.97      | 0.97                                   | 0.92 | 0.92                                   | 0.92 |
| 1                                                                                                                                                                 | 0.94                                                                                |                                                                                                                                         |                                                                                     | 0.90        | 0.86         | 0.92 | 0.88        | 0.84         | 0.84 | 0.81      | 0.79                                   | 0.81 | 0.79                                   | 0.76 |
| 2                                                                                                                                                                 | 0.85                                                                                |                                                                                                                                         |                                                                                     | 0.78        | 0.72         | 0.83 | 0.76        | 0.70         | 0.73 | 0.68      | 0.64                                   | 0.70 | 0.66                                   | 0.63 |
| 3                                                                                                                                                                 | 0.77                                                                                |                                                                                                                                         |                                                                                     | 0.68        | 0.60         | 0.75 | 0.66        | 0.59         | 0.64 | 0.58      | 0.53                                   | 0.61 | 0.56                                   | 0.52 |
| 4                                                                                                                                                                 | 0.70                                                                                |                                                                                                                                         |                                                                                     | 0.60        | 0.52         | 0.68 | 0.58        | 0.51         | 0.56 | 0.50      | 0.45                                   | 0.54 | 0.48                                   | 0.44 |
| 5                                                                                                                                                                 | 0.65                                                                                |                                                                                                                                         |                                                                                     | 0.53        | 0.45         | 0.63 | 0.52        | 0.44         | 0.50 | 0.43      | 0.38                                   | 0.48 | 0.42                                   | 0.38 |
| 6                                                                                                                                                                 | 0.59                                                                                |                                                                                                                                         |                                                                                     | 0.47        | 0.39         | 0.58 | 0.47        | 0.39         | 0.45 | 0.38      | 0.33                                   | 0.43 | 0.37                                   | 0.33 |
| 7                                                                                                                                                                 | 0.55                                                                                |                                                                                                                                         |                                                                                     | 0.43        | 0.35         | 0.53 | 0.42        | 0.35         | 0.41 | 0.34      | 0.29                                   | 0.39 | 0.33                                   | 0.29 |
| 8                                                                                                                                                                 | 0.51                                                                                |                                                                                                                                         |                                                                                     | 0.39        | 0.31         | 0.50 | 0.38        | 0.31         | 0.37 | 0.30      | 0.26                                   | 0.36 | 0.30                                   | 0.26 |
| 9                                                                                                                                                                 | 0.48                                                                                |                                                                                                                                         |                                                                                     | 0.36        | 0.28         | 0.46 | 0.35        | 0.28         | 0.34 | 0.28      | 0.23                                   | 0.33 | 0.27                                   | 0.23 |
| 10                                                                                                                                                                | 0.45                                                                                |                                                                                                                                         |                                                                                     | 0.33        | 0.26         | 0.43 | 0.32        | 0.25         | 0.31 | 0.25      | 0.21                                   | 0.31 | 0.25                                   | 0.21 |
| <br>2-Lamp bare strip                                                          |  | EFF = 89.3%                                                                                                                             |                                                                                     |             | % DN = 86.4% |      |             | % UP = 13.6% |      |           | Lamp = (2) F40T1<br>SC (along, across) |      |                                        |      |
|                                                                                                                                                                   |                                                                                     | 0                                                                                                                                       | 1.03                                                                                | 1.03        | 1.03         | 1.00 | 1.00        | 1.00         | 0.92 | 0.92      | 0.92                                   | 0.86 | 0.86                                   | 0.86 |
|                                                                                                                                                                   |                                                                                     | 1                                                                                                                                       | 0.93                                                                                | 0.88        | 0.83         | 0.89 | 0.84        | 0.80         | 0.78 | 0.75      | 0.72                                   | 0.73 | 0.70                                   | 0.68 |
|                                                                                                                                                                   |                                                                                     | 2                                                                                                                                       | 0.83                                                                                | 0.75        | 0.68         | 0.80 | 0.72        | 0.66         | 0.67 | 0.62      | 0.58                                   | 0.62 | 0.58                                   | 0.55 |
|                                                                                                                                                                   |                                                                                     | 3                                                                                                                                       | 0.75                                                                                | 0.65        | 0.57         | 0.72 | 0.63        | 0.56         | 0.58 | 0.52      | 0.47                                   | 0.54 | 0.49                                   | 0.45 |
|                                                                                                                                                                   |                                                                                     | 4                                                                                                                                       | 0.69                                                                                | 0.57        | 0.49         | 0.65 | 0.55        | 0.47         | 0.51 | 0.45      | 0.40                                   | 0.48 | 0.42                                   | 0.38 |
|                                                                                                                                                                   |                                                                                     | 5                                                                                                                                       | 0.63                                                                                | 0.51        | 0.42         | 0.60 | 0.49        | 0.41         | 0.46 | 0.39      | 0.34                                   | 0.43 | 0.37                                   | 0.32 |
|                                                                                                                                                                   |                                                                                     | 6                                                                                                                                       | 0.58                                                                                | 0.45        | 0.37         | 0.55 | 0.44        | 0.36         | 0.41 | 0.34      | 0.29                                   | 0.38 | 0.32                                   | 0.28 |
|                                                                                                                                                                   |                                                                                     | 7                                                                                                                                       | 0.53                                                                                | 0.41        | 0.33         | 0.51 | 0.40        | 0.32         | 0.37 | 0.30      | 0.26                                   | 0.35 | 0.29                                   | 0.25 |
|                                                                                                                                                                   |                                                                                     | 8                                                                                                                                       | 0.50                                                                                | 0.37        | 0.29         | 0.47 | 0.36        | 0.29         | 0.34 | 0.27      | 0.23                                   | 0.32 | 0.26                                   | 0.22 |
|                                                                                                                                                                   |                                                                                     | 9                                                                                                                                       | 0.46                                                                                | 0.34        | 0.26         | 0.44 | 0.33        | 0.26         | 0.31 | 0.25      | 0.20                                   | 0.29 | 0.24                                   | 0.19 |
|                                                                                                                                                                   |                                                                                     | 10                                                                                                                                      | 0.43                                                                                | 0.31        | 0.24         | 0.41 | 0.30        | 0.23         | 0.29 | 0.22      | 0.18                                   | 0.27 | 0.21                                   | 0.18 |
| <br>2 x 4, 3-Lamp parabolic troffer<br>with 3" semi-spec. louvers, 18<br>cells |  | EFF = 72.7%                                                                                                                             |                                                                                     |             | % DN = 100   |      |             | % UP = 0     |      |           | Lamp = (3) F32T8<br>SC (along, across) |      |                                        |      |
|                                                                                                                                                                   |                                                                                     | 0                                                                                                                                       | 0.87                                                                                | 0.87        | 0.87         | 0.85 | 0.85        | 0.85         | 0.81 | 0.81      | 0.81                                   | 0.77 | 0.77                                   | 0.77 |
|                                                                                                                                                                   |                                                                                     | 1                                                                                                                                       | 0.81                                                                                | 0.78        | 0.76         | 0.79 | 0.77        | 0.74         | 0.74 | 0.72      | 0.70                                   | 0.71 | 0.69                                   | 0.68 |
|                                                                                                                                                                   |                                                                                     | 2                                                                                                                                       | 0.75                                                                                | 0.70        | 0.66         | 0.73 | 0.69        | 0.65         | 0.66 | 0.63      | 0.61                                   | 0.64 | 0.61                                   | 0.58 |
|                                                                                                                                                                   |                                                                                     | 3                                                                                                                                       | 0.69                                                                                | 0.63        | 0.58         | 0.68 | 0.62        | 0.57         | 0.60 | 0.56      | 0.52                                   | 0.58 | 0.54                                   | 0.52 |
|                                                                                                                                                                   |                                                                                     | 4                                                                                                                                       | 0.64                                                                                | 0.56        | 0.51         | 0.62 | 0.55        | 0.50         | 0.54 | 0.49      | 0.46                                   | 0.52 | 0.48                                   | 0.45 |
|                                                                                                                                                                   |                                                                                     | 5                                                                                                                                       | 0.59                                                                                | 0.51        | 0.45         | 0.58 | 0.50        | 0.44         | 0.48 | 0.44      | 0.40                                   | 0.47 | 0.43                                   | 0.40 |
|                                                                                                                                                                   |                                                                                     | 6                                                                                                                                       | 0.55                                                                                | 0.46        | 0.40         | 0.53 | 0.45        | 0.40         | 0.44 | 0.39      | 0.35                                   | 0.43 | 0.38                                   | 0.35 |
|                                                                                                                                                                   |                                                                                     | 7                                                                                                                                       | 0.51                                                                                | 0.42        | 0.36         | 0.50 | 0.41        | 0.36         | 0.40 | 0.35      | 0.31                                   | 0.39 | 0.35                                   | 0.31 |
|                                                                                                                                                                   |                                                                                     | 8                                                                                                                                       | 0.47                                                                                | 0.38        | 0.32         | 0.46 | 0.38        | 0.32         | 0.37 | 0.32      | 0.28                                   | 0.36 | 0.31                                   | 0.28 |
|                                                                                                                                                                   |                                                                                     | 9                                                                                                                                       | 0.44                                                                                | 0.35        | 0.29         | 0.43 | 0.35        | 0.29         | 0.34 | 0.29      | 0.25                                   | 0.33 | 0.29                                   | 0.25 |
|                                                                                                                                                                   |                                                                                     | 10                                                                                                                                      | 0.41                                                                                | 0.32        | 0.27         | 0.40 | 0.32        | 0.27         | 0.31 | 0.26      | 0.23                                   | 0.31 | 0.26                                   | 0.23 |
|                                                                                |  | EFF = 88.3%                                                                                                                             |                                                                                     |             | % DN = 100   |      |             | % UP = 0     |      |           | Lamp = (3) F40T1<br>SC (along, across) |      |                                        |      |
|                                                                                                                                                                   |                                                                                     | 0                                                                                                                                       | 1.03                                                                                | 1.03        | 1.03         | 1.00 | 1.00        | 1.00         | 0.92 | 0.92      | 0.92                                   | 0.86 | 0.86                                   | 0.86 |
|                                                                                                                                                                   |                                                                                     | 1                                                                                                                                       | 0.93                                                                                | 0.88        | 0.83         | 0.89 | 0.84        | 0.80         | 0.78 | 0.75      | 0.72                                   | 0.73 | 0.70                                   | 0.68 |
|                                                                                                                                                                   |                                                                                     | 2                                                                                                                                       | 0.83                                                                                | 0.75        | 0.68         | 0.80 | 0.72        | 0.66         | 0.67 | 0.62      | 0.58                                   | 0.62 | 0.58                                   | 0.55 |
|                                                                                                                                                                   |                                                                                     | 3                                                                                                                                       | 0.75                                                                                | 0.65        | 0.57         | 0.72 | 0.63        | 0.56         | 0.58 | 0.52      | 0.47                                   | 0.54 | 0.49                                   | 0.45 |
|                                                                                                                                                                   |                                                                                     | 4                                                                                                                                       | 0.69                                                                                | 0.57        | 0.49         | 0.65 | 0.55        | 0.47         | 0.51 | 0.45      | 0.40                                   | 0.48 | 0.42                                   | 0.38 |
|                                                                                                                                                                   |                                                                                     | 5                                                                                                                                       | 0.63                                                                                | 0.51        | 0.42         | 0.60 | 0.49        | 0.41         | 0.46 | 0.39      | 0.34                                   | 0.43 | 0.37                                   | 0.32 |
|                                                                                                                                                                   |                                                                                     | 6                                                                                                                                       | 0.58                                                                                | 0.45        | 0.37         | 0.55 | 0.44        | 0.36         | 0.41 | 0.34      | 0.29                                   | 0.38 | 0.32                                   | 0.28 |
|                                                                                                                                                                   |                                                                                     | 7                                                                                                                                       | 0.53                                                                                | 0.41        | 0.33         | 0.51 | 0.40        | 0.32         | 0.37 | 0.30      | 0.26                                   | 0.35 | 0.29                                   | 0.25 |
|                                                                                                                                                                   |                                                                                     | 8                                                                                                                                       | 0.50                                                                                | 0.37        | 0.29         | 0.47 | 0.36        | 0.29         | 0.34 | 0.27      | 0.23                                   | 0.32 | 0.26                                   | 0.22 |
|                                                                                                                                                                   |                                                                                     | 9                                                                                                                                       | 0.46                                                                                | 0.34        | 0.26         | 0.44 | 0.33        | 0.26         | 0.31 | 0.25      | 0.20                                   | 0.29 | 0.24                                   | 0.19 |
|                                                                                                                                                                   |                                                                                     | 10                                                                                                                                      | 0.43                                                                                | 0.31        | 0.24         | 0.41 | 0.30        | 0.23         | 0.29 | 0.22      | 0.18                                   | 0.27 | 0.21                                   | 0.18 |

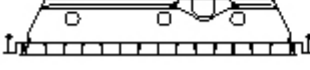
2 x 4, 3-Lamp parabolic troffer  
with 4" semi-spec. louvers, 18  
cells

|    | EFF = 66.2% |      |      | % DN = 100 |      |      | % UP = 0 |      |      | SC (along, across) |      |      |
|----|-------------|------|------|------------|------|------|----------|------|------|--------------------|------|------|
| 0  | 0.79        | 0.79 | 0.79 | 0.77       | 0.77 | 0.77 | 0.74     | 0.74 | 0.74 | 0.70               | 0.70 | 0.70 |
| 1  | 0.74        | 0.72 | 0.69 | 0.72       | 0.70 | 0.68 | 0.67     | 0.66 | 0.64 | 0.65               | 0.64 | 0.62 |
| 2  | 0.69        | 0.64 | 0.61 | 0.67       | 0.63 | 0.60 | 0.61     | 0.58 | 0.56 | 0.59               | 0.57 | 0.55 |
| 3  | 0.63        | 0.58 | 0.53 | 0.62       | 0.57 | 0.53 | 0.55     | 0.51 | 0.48 | 0.53               | 0.50 | 0.48 |
| 4  | 0.59        | 0.52 | 0.47 | 0.57       | 0.51 | 0.47 | 0.50     | 0.46 | 0.42 | 0.48               | 0.45 | 0.42 |
| 5  | 0.54        | 0.47 | 0.42 | 0.53       | 0.46 | 0.41 | 0.45     | 0.41 | 0.37 | 0.44               | 0.40 | 0.37 |
| 6  | 0.50        | 0.43 | 0.37 | 0.49       | 0.42 | 0.37 | 0.41     | 0.36 | 0.33 | 0.40               | 0.36 | 0.33 |
| 7  | 0.47        | 0.39 | 0.33 | 0.46       | 0.38 | 0.33 | 0.37     | 0.33 | 0.30 | 0.36               | 0.32 | 0.29 |
| 8  | 0.44        | 0.35 | 0.30 | 0.43       | 0.35 | 0.30 | 0.34     | 0.30 | 0.26 | 0.33               | 0.29 | 0.26 |
| 9  | 0.41        | 0.33 | 0.27 | 0.40       | 0.32 | 0.27 | 0.31     | 0.27 | 0.24 | 0.31               | 0.27 | 0.24 |
| 10 | 0.38        | 0.30 | 0.25 | 0.37       | 0.30 | 0.25 | 0.29     | 0.25 | 0.22 | 0.28               | 0.24 | 0.22 |

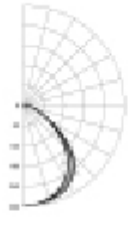
Figure 9-28 Continued

| Typical Luminaire                                                                                                                                              | Typical Intensity Distribution                                                      | $\rho_{cc} \rightarrow$ | 80          |      |             | 70          |      |           | 50        |      |                                        | 30                                    |      |      |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-------------------------|-------------|------|-------------|-------------|------|-----------|-----------|------|----------------------------------------|---------------------------------------|------|------|
|                                                                                                                                                                |                                                                                     | $\rho_w \rightarrow$    | 70          | 50   | 30          | 70          | 50   | 30        | 50        | 30   | 10                                     | 50                                    | 30   | 10   |
|                                                                                                                                                                |                                                                                     | RCR<br>$\downarrow$     | EFF = 67.8% |      |             | % DN = 100% |      |           | % UP = 0% |      |                                        | Lamp = (3) FT40<br>SC (along, across) |      |      |
| <br>2 x 2, 3-Lamp with 3" semi-spec. louvers, 9 cells                         |    | 0                       | 0.81        | 0.81 | 0.81        | 0.79        | 0.79 | 0.79      | 0.75      | 0.75 | 0.75                                   | 0.72                                  | 0.72 | 0.72 |
|                                                                                                                                                                |                                                                                     | 1                       | 0.75        | 0.73 | 0.71        | 0.74        | 0.71 | 0.69      | 0.69      | 0.67 | 0.66                                   | 0.66                                  | 0.65 | 0.64 |
|                                                                                                                                                                |                                                                                     | 2                       | 0.70        | 0.65 | 0.62        | 0.68        | 0.64 | 0.61      | 0.62      | 0.59 | 0.57                                   | 0.60                                  | 0.57 | 0.54 |
|                                                                                                                                                                |                                                                                     | 3                       | 0.65        | 0.59 | 0.54        | 0.63        | 0.58 | 0.53      | 0.56      | 0.52 | 0.49                                   | 0.54                                  | 0.51 | 0.48 |
|                                                                                                                                                                |                                                                                     | 4                       | 0.60        | 0.53 | 0.48        | 0.58        | 0.52 | 0.47      | 0.50      | 0.46 | 0.43                                   | 0.49                                  | 0.45 | 0.42 |
|                                                                                                                                                                |                                                                                     | 5                       | 0.55        | 0.47 | 0.42        | 0.54        | 0.47 | 0.42      | 0.45      | 0.41 | 0.38                                   | 0.44                                  | 0.40 | 0.37 |
|                                                                                                                                                                |                                                                                     | 6                       | 0.51        | 0.43 | 0.38        | 0.50        | 0.42 | 0.37      | 0.41      | 0.37 | 0.33                                   | 0.40                                  | 0.36 | 0.33 |
|                                                                                                                                                                |                                                                                     | 7                       | 0.47        | 0.39 | 0.34        | 0.46        | 0.39 | 0.33      | 0.38      | 0.33 | 0.30                                   | 0.37                                  | 0.32 | 0.29 |
|                                                                                                                                                                |                                                                                     | 8                       | 0.44        | 0.36 | 0.30        | 0.43        | 0.35 | 0.30      | 0.34      | 0.30 | 0.27                                   | 0.34                                  | 0.29 | 0.26 |
|                                                                                                                                                                |                                                                                     | 9                       | 0.41        | 0.33 | 0.28        | 0.40        | 0.32 | 0.27      | 0.32      | 0.27 | 0.24                                   | 0.31                                  | 0.27 | 0.24 |
|                                                                                                                                                                |                                                                                     | 10                      | 0.39        | 0.30 | 0.25        | 0.38        | 0.30 | 0.25      | 0.29      | 0.25 | 0.22                                   | 0.29                                  | 0.25 | 0.22 |
| <br>2 x 2, 2-Lamp (U) parabolic troffer with 3" semi-spec. louver, 16 cells |  | EFF = 50.8%             |             |      | % DN = 100% |             |      | % UP = 0% |           |      | Lamp = (2) F31T1<br>SC (along, across) |                                       |      |      |
|                                                                                                                                                                |                                                                                     | 0                       | 0.61        | 0.61 | 0.61        | 0.59        | 0.59 | 0.59      | 0.56      | 0.56 | 0.56                                   | 0.56                                  | 0.56 | 0.56 |
|                                                                                                                                                                |                                                                                     | 1                       | 0.57        | 0.55 | 0.53        | 0.55        | 0.54 | 0.52      | 0.52      | 0.50 | 0.49                                   | 0.52                                  | 0.50 | 0.48 |
|                                                                                                                                                                |                                                                                     | 2                       | 0.53        | 0.49 | 0.47        | 0.51        | 0.48 | 0.46      | 0.47      | 0.45 | 0.43                                   | 0.47                                  | 0.45 | 0.43 |
|                                                                                                                                                                |                                                                                     | 3                       | 0.49        | 0.44 | 0.41        | 0.48        | 0.43 | 0.40      | 0.42      | 0.39 | 0.37                                   | 0.42                                  | 0.39 | 0.37 |
|                                                                                                                                                                |                                                                                     | 4                       | 0.45        | 0.40 | 0.36        | 0.44        | 0.39 | 0.36      | 0.38      | 0.35 | 0.32                                   | 0.38                                  | 0.35 | 0.33 |
|                                                                                                                                                                |                                                                                     | 5                       | 0.42        | 0.36 | 0.32        | 0.41        | 0.35 | 0.32      | 0.34      | 0.31 | 0.29                                   | 0.34                                  | 0.31 | 0.29 |
|                                                                                                                                                                |                                                                                     | 6                       | 0.39        | 0.33 | 0.29        | 0.38        | 0.32 | 0.28      | 0.31      | 0.28 | 0.25                                   | 0.31                                  | 0.28 | 0.25 |
|                                                                                                                                                                |                                                                                     | 7                       | 0.36        | 0.30 | 0.26        | 0.35        | 0.29 | 0.25      | 0.29      | 0.25 | 0.23                                   | 0.29                                  | 0.25 | 0.23 |
|                                                                                                                                                                |                                                                                     | 8                       | 0.33        | 0.27 | 0.23        | 0.33        | 0.27 | 0.23      | 0.26      | 0.23 | 0.20                                   | 0.26                                  | 0.23 | 0.20 |
|                                                                                                                                                                |                                                                                     | 9                       | 0.31        | 0.25 | 0.21        | 0.31        | 0.25 | 0.21      | 0.24      | 0.21 | 0.18                                   | 0.24                                  | 0.21 | 0.18 |
| 10                                                                                                                                                             | 0.29                                                                                | 0.23                    | 0.19        | 0.29 | 0.23        | 0.19        | 0.22 | 0.19      | 0.17      | 0.22 | 0.19                                   | 0.17                                  |      |      |
| <br>1 x 4, 2-Lamp parabolic troffer with 3" semi-spec. louver, 8 or 9 cells |  | EFF = 67.2%             |             |      | % DN = 100% |             |      | % UP = 0% |           |      | Lamp = (2) F32T1<br>SC (along, across) |                                       |      |      |
|                                                                                                                                                                |                                                                                     | 0                       | 0.80        | 0.80 | 0.80        | 0.78        | 0.78 | 0.78      | 0.75      | 0.75 | 0.75                                   | 0.72                                  | 0.72 | 0.72 |
|                                                                                                                                                                |                                                                                     | 1                       | 0.75        | 0.73 | 0.70        | 0.73        | 0.71 | 0.69      | 0.68      | 0.67 | 0.65                                   | 0.66                                  | 0.64 | 0.63 |
|                                                                                                                                                                |                                                                                     | 2                       | 0.70        | 0.65 | 0.61        | 0.68        | 0.64 | 0.61      | 0.62      | 0.59 | 0.56                                   | 0.59                                  | 0.57 | 0.54 |
|                                                                                                                                                                |                                                                                     | 3                       | 0.64        | 0.58 | 0.54        | 0.63        | 0.57 | 0.53      | 0.55      | 0.52 | 0.49                                   | 0.54                                  | 0.51 | 0.48 |
|                                                                                                                                                                |                                                                                     | 4                       | 0.59        | 0.52 | 0.47        | 0.58        | 0.52 | 0.47      | 0.50      | 0.46 | 0.43                                   | 0.49                                  | 0.45 | 0.42 |
|                                                                                                                                                                |                                                                                     | 5                       | 0.55        | 0.47 | 0.42        | 0.54        | 0.47 | 0.42      | 0.45      | 0.41 | 0.37                                   | 0.44                                  | 0.40 | 0.37 |
|                                                                                                                                                                |                                                                                     | 6                       | 0.51        | 0.43 | 0.37        | 0.50        | 0.42 | 0.37      | 0.41      | 0.36 | 0.33                                   | 0.40                                  | 0.36 | 0.33 |
|                                                                                                                                                                |                                                                                     | 7                       | 0.47        | 0.39 | 0.34        | 0.46        | 0.38 | 0.33      | 0.37      | 0.33 | 0.29                                   | 0.36                                  | 0.32 | 0.29 |
|                                                                                                                                                                |                                                                                     | 8                       | 0.44        | 0.36 | 0.30        | 0.43        | 0.35 | 0.30      | 0.34      | 0.30 | 0.26                                   | 0.33                                  | 0.29 | 0.26 |
|                                                                                                                                                                |                                                                                     | 9                       | 0.41        | 0.33 | 0.27        | 0.40        | 0.32 | 0.27      | 0.31      | 0.27 | 0.24                                   | 0.31                                  | 0.27 | 0.24 |
| 10                                                                                                                                                             | 0.38                                                                                | 0.30                    | 0.25        | 0.38 | 0.30        | 0.25        | 0.29 | 0.25      | 0.22      | 0.28 | 0.24                                   | 0.22                                  |      |      |
| <br>2 x 4, 3-Lamp parabolic troffer, spec. louvers, 18 cells, RP-1          |  | EFF = 67.2%             |             |      | % DN = 100  |             |      | % UP = 0  |           |      | Lamp = (3) F32T1<br>SC (along, across) |                                       |      |      |
|                                                                                                                                                                |                                                                                     | 0                       | 0.80        | 0.80 | 0.80        | 0.78        | 0.78 | 0.78      | 0.75      | 0.75 | 0.75                                   | 0.72                                  | 0.72 | 0.72 |
|                                                                                                                                                                |                                                                                     | 1                       | 0.76        | 0.74 | 0.72        | 0.74        | 0.72 | 0.70      | 0.69      | 0.68 | 0.67                                   | 0.67                                  | 0.66 | 0.64 |
|                                                                                                                                                                |                                                                                     | 2                       | 0.71        | 0.67 | 0.64        | 0.70        | 0.66 | 0.63      | 0.64      | 0.62 | 0.59                                   | 0.62                                  | 0.60 | 0.58 |
|                                                                                                                                                                |                                                                                     | 3                       | 0.67        | 0.62 | 0.58        | 0.65        | 0.61 | 0.57      | 0.59      | 0.56 | 0.53                                   | 0.57                                  | 0.54 | 0.52 |
|                                                                                                                                                                |                                                                                     | 4                       | 0.62        | 0.56 | 0.52        | 0.61        | 0.56 | 0.51      | 0.54      | 0.50 | 0.48                                   | 0.53                                  | 0.50 | 0.47 |
|                                                                                                                                                                |                                                                                     | 5                       | 0.58        | 0.52 | 0.47        | 0.57        | 0.51 | 0.47      | 0.50      | 0.46 | 0.43                                   | 0.49                                  | 0.45 | 0.43 |
|                                                                                                                                                                |                                                                                     | 6                       | 0.55        | 0.47 | 0.43        | 0.53        | 0.47 | 0.42      | 0.46      | 0.42 | 0.39                                   | 0.45                                  | 0.41 | 0.38 |
|                                                                                                                                                                |                                                                                     | 7                       | 0.51        | 0.44 | 0.39        | 0.50        | 0.43 | 0.39      | 0.42      | 0.38 | 0.35                                   | 0.41                                  | 0.38 | 0.34 |
|                                                                                                                                                                |                                                                                     | 8                       | 0.48        | 0.40 | 0.36        | 0.47        | 0.40 | 0.35      | 0.39      | 0.35 | 0.32                                   | 0.38                                  | 0.35 | 0.32 |
|                                                                                                                                                                |                                                                                     | 9                       | 0.45        | 0.37 | 0.33        | 0.44        | 0.37 | 0.32      | 0.36      | 0.32 | 0.29                                   | 0.36                                  | 0.32 | 0.29 |
| 10                                                                                                                                                             | 0.42                                                                                | 0.35                    | 0.30        | 0.42 | 0.34        | 0.30        | 0.34 | 0.30      | 0.27      | 0.33 | 0.29                                   | 0.27                                  |      |      |

30

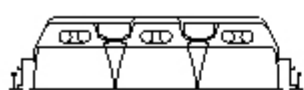
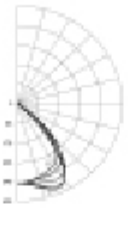
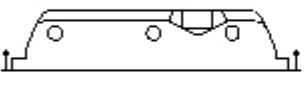
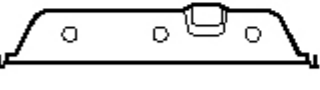
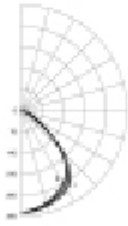
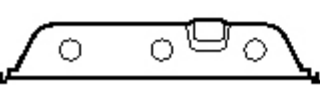
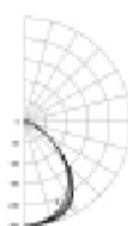


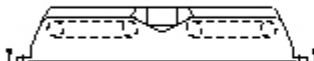
2 × 4, 3-Lamp parabolic troffer,  
1.5 × 1.5 × 1.0" silver louvers,  
RP-1



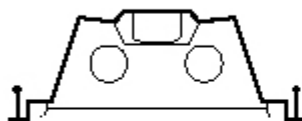
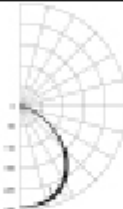
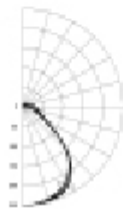
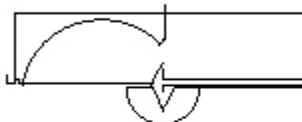
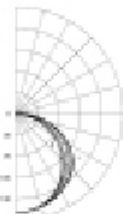
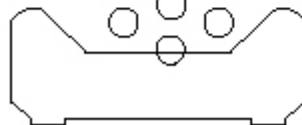
|    | EFF = 51.4% |      |      | % DN = 100 |      |      | % UP = 0 |      |      | Lamp = (3) F32T8<br>SC (along, across) |      |      |
|----|-------------|------|------|------------|------|------|----------|------|------|----------------------------------------|------|------|
|    | 0           | 1    | 2    | 3          | 4    | 5    | 6        | 7    | 8    | 9                                      | 10   |      |
| 0  | 0.68        | 0.61 | 0.55 | 0.67       | 0.60 | 0.55 | 0.58     | 0.53 | 0.50 | 0.56                                   | 0.52 | 0.48 |
| 1  | 0.63        | 0.55 | 0.49 | 0.61       | 0.54 | 0.48 | 0.52     | 0.47 | 0.43 | 0.50                                   | 0.46 | 0.42 |
| 2  | 0.58        | 0.49 | 0.43 | 0.57       | 0.48 | 0.42 | 0.47     | 0.42 | 0.38 | 0.45                                   | 0.41 | 0.37 |
| 3  | 0.54        | 0.44 | 0.38 | 0.52       | 0.44 | 0.38 | 0.42     | 0.37 | 0.33 | 0.41                                   | 0.37 | 0.33 |
| 4  | 0.50        | 0.40 | 0.34 | 0.49       | 0.40 | 0.34 | 0.39     | 0.34 | 0.30 | 0.38                                   | 0.33 | 0.29 |
| 5  | 0.47        | 0.37 | 0.31 | 0.46       | 0.37 | 0.31 | 0.36     | 0.30 | 0.27 | 0.35                                   | 0.30 | 0.26 |
| 6  | 0.44        | 0.34 | 0.28 | 0.43       | 0.34 | 0.28 | 0.33     | 0.28 | 0.24 | 0.32                                   | 0.27 | 0.24 |
| 7  | 0.41        | 0.32 | 0.26 | 0.40       | 0.31 | 0.26 | 0.30     | 0.25 | 0.22 | 0.30                                   | 0.25 | 0.22 |
| 8  | 0.00        | 0.00 | 0.00 | 0.00       | 0.00 | 0.00 | 0.00     | 0.00 | 0.00 | 0.00                                   | 0.00 | 0.00 |
| 9  | 0.00        | 0.00 | 0.00 | 0.00       | 0.00 | 0.00 | 0.00     | 0.00 | 0.00 | 0.00                                   | 0.00 | 0.00 |
| 10 | 0.77        | 0.77 | 0.77 | 0.76       | 0.76 | 0.76 | 0.72     | 0.72 | 0.72 | 0.69                                   | 0.69 | 0.68 |

Figure 9-28 Continued

| Typical Luminaire                                                                                                                         | Typical Intensity Distribution                                                      | pcc →       |             |      | 80          |             |      | 70        |           |      | 50                                     |                                        |      | 30   |    |    |
|-------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-------------|-------------|------|-------------|-------------|------|-----------|-----------|------|----------------------------------------|----------------------------------------|------|------|----|----|
|                                                                                                                                           |                                                                                     | ρw →        |             |      | 70          | 50          | 30   | 70        | 50        | 30   | 50                                     | 30                                     | 10   | 50   | 30 | 10 |
|                                                                                                                                           |                                                                                     | RCR ↓       | EFF = 64.6% |      |             | % DN = 100% |      |           | % UP = 0% |      |                                        | Lamp = (3) F31T8<br>SC (along, across) |      |      |    |    |
| <br>2 × 2, 3-Lamp troffer, spec. louvers, 12 cells, RP-1 |   | 0           | 0.77        | 0.77 | 0.77        | 0.75        | 0.75 | 0.75      | 0.72      | 0.72 | 0.72                                   | 0.69                                   | 0.69 | 0.69 |    |    |
|                                                                                                                                           |                                                                                     | 1           | 0.73        | 0.71 | 0.69        | 0.71        | 0.69 | 0.68      | 0.67      | 0.65 | 0.64                                   | 0.64                                   | 0.63 | 0.62 |    |    |
|                                                                                                                                           |                                                                                     | 2           | 0.68        | 0.65 | 0.62        | 0.67        | 0.64 | 0.61      | 0.61      | 0.59 | 0.57                                   | 0.59                                   | 0.58 | 0.56 |    |    |
|                                                                                                                                           |                                                                                     | 3           | 0.64        | 0.59 | 0.55        | 0.63        | 0.58 | 0.55      | 0.56      | 0.54 | 0.51                                   | 0.55                                   | 0.52 | 0.50 |    |    |
|                                                                                                                                           |                                                                                     | 4           | 0.60        | 0.54 | 0.50        | 0.59        | 0.53 | 0.50      | 0.52      | 0.49 | 0.46                                   | 0.51                                   | 0.48 | 0.45 |    |    |
|                                                                                                                                           |                                                                                     | 5           | 0.56        | 0.50 | 0.45        | 0.55        | 0.49 | 0.45      | 0.48      | 0.44 | 0.41                                   | 0.47                                   | 0.43 | 0.41 |    |    |
|                                                                                                                                           |                                                                                     | 6           | 0.53        | 0.46 | 0.41        | 0.51        | 0.45 | 0.41      | 0.44      | 0.40 | 0.37                                   | 0.43                                   | 0.40 | 0.37 |    |    |
|                                                                                                                                           |                                                                                     | 7           | 0.49        | 0.42 | 0.38        | 0.48        | 0.42 | 0.37      | 0.41      | 0.37 | 0.34                                   | 0.40                                   | 0.36 | 0.34 |    |    |
|                                                                                                                                           |                                                                                     | 8           | 0.46        | 0.39 | 0.34        | 0.45        | 0.39 | 0.34      | 0.38      | 0.34 | 0.31                                   | 0.37                                   | 0.33 | 0.31 |    |    |
|                                                                                                                                           |                                                                                     | 9           | 0.43        | 0.36 | 0.32        | 0.43        | 0.36 | 0.31      | 0.35      | 0.31 | 0.28                                   | 0.34                                   | 0.31 | 0.28 |    |    |
|                                                                                                                                           |                                                                                     | 10          | 0.41        | 0.33 | 0.29        | 0.40        | 0.33 | 0.29      | 0.33      | 0.29 | 0.26                                   | 0.32                                   | 0.28 | 0.26 |    |    |
| <br>2 × 4, 3-Lamp troffer with A12 lens                |  | EFF = 75.6% |             |      | % DN = 100% |             |      | % UP = 0% |           |      | Lamp = (3) F32T8<br>SC (along, across) |                                        |      |      |    |    |
|                                                                                                                                           |                                                                                     | 0           | 0.90        | 0.90 | 0.90        | 0.88        | 0.88 | 0.88      | 0.84      | 0.84 | 0.84                                   | 0.80                                   | 0.80 | 0.80 |    |    |
|                                                                                                                                           |                                                                                     | 1           | 0.83        | 0.79 | 0.76        | 0.81        | 0.78 | 0.75      | 0.75      | 0.72 | 0.70                                   | 0.72                                   | 0.70 | 0.68 |    |    |
|                                                                                                                                           |                                                                                     | 2           | 0.76        | 0.70 | 0.65        | 0.74        | 0.69 | 0.64      | 0.66      | 0.62 | 0.59                                   | 0.64                                   | 0.61 | 0.58 |    |    |
|                                                                                                                                           |                                                                                     | 3           | 0.70        | 0.62 | 0.57        | 0.68        | 0.61 | 0.56      | 0.59      | 0.54 | 0.51                                   | 0.57                                   | 0.53 | 0.50 |    |    |
|                                                                                                                                           |                                                                                     | 4           | 0.64        | 0.56 | 0.49        | 0.63        | 0.55 | 0.49      | 0.53      | 0.48 | 0.44                                   | 0.51                                   | 0.47 | 0.43 |    |    |
|                                                                                                                                           |                                                                                     | 5           | 0.59        | 0.50 | 0.44        | 0.58        | 0.49 | 0.43      | 0.48      | 0.42 | 0.38                                   | 0.46                                   | 0.41 | 0.38 |    |    |
|                                                                                                                                           |                                                                                     | 6           | 0.55        | 0.45 | 0.39        | 0.53        | 0.45 | 0.38      | 0.43      | 0.38 | 0.34                                   | 0.42                                   | 0.37 | 0.33 |    |    |
|                                                                                                                                           |                                                                                     | 7           | 0.51        | 0.41 | 0.35        | 0.50        | 0.41 | 0.35      | 0.39      | 0.34 | 0.30                                   | 0.38                                   | 0.33 | 0.30 |    |    |
|                                                                                                                                           |                                                                                     | 8           | 0.48        | 0.38 | 0.31        | 0.46        | 0.37 | 0.31      | 0.36      | 0.31 | 0.27                                   | 0.35                                   | 0.30 | 0.27 |    |    |
|                                                                                                                                           |                                                                                     | 9           | 0.44        | 0.35 | 0.29        | 0.43        | 0.34 | 0.28      | 0.33      | 0.28 | 0.24                                   | 0.33                                   | 0.28 | 0.24 |    |    |
| 10                                                                                                                                        | 0.42                                                                                | 0.32        | 0.26        | 0.41 | 0.32        | 0.26        | 0.31 | 0.26      | 0.22      | 0.30 | 0.25                                   | 0.22                                   |      |      |    |    |
| <br>2 × 4, 3-Lamp troffer with A19 lens                |  | EFF = 72.4% |             |      | % DN = 100% |             |      | % UP = 0% |           |      | Lamp = (3) F32T8<br>SC (along, across) |                                        |      |      |    |    |
|                                                                                                                                           |                                                                                     | 0           | 0.86        | 0.86 | 0.86        | 0.84        | 0.84 | 0.84      | 0.80      | 0.80 | 0.80                                   | 0.77                                   | 0.77 | 0.77 |    |    |
|                                                                                                                                           |                                                                                     | 1           | 0.80        | 0.77 | 0.75        | 0.78        | 0.76 | 0.73      | 0.73      | 0.71 | 0.69                                   | 0.70                                   | 0.68 | 0.67 |    |    |
|                                                                                                                                           |                                                                                     | 2           | 0.74        | 0.69 | 0.65        | 0.72        | 0.68 | 0.64      | 0.65      | 0.62 | 0.59                                   | 0.63                                   | 0.60 | 0.58 |    |    |
|                                                                                                                                           |                                                                                     | 3           | 0.69        | 0.62 | 0.57        | 0.67        | 0.61 | 0.56      | 0.59      | 0.55 | 0.52                                   | 0.57                                   | 0.54 | 0.51 |    |    |
|                                                                                                                                           |                                                                                     | 4           | 0.64        | 0.56 | 0.50        | 0.62        | 0.55 | 0.50      | 0.53      | 0.49 | 0.45                                   | 0.52                                   | 0.48 | 0.44 |    |    |
|                                                                                                                                           |                                                                                     | 5           | 0.59        | 0.51 | 0.45        | 0.58        | 0.50 | 0.45      | 0.48      | 0.44 | 0.40                                   | 0.47                                   | 0.43 | 0.40 |    |    |
|                                                                                                                                           |                                                                                     | 6           | 0.55        | 0.46 | 0.40        | 0.54        | 0.45 | 0.40      | 0.44      | 0.39 | 0.36                                   | 0.43                                   | 0.39 | 0.36 |    |    |
|                                                                                                                                           |                                                                                     | 7           | 0.51        | 0.42 | 0.36        | 0.50        | 0.42 | 0.36      | 0.41      | 0.36 | 0.32                                   | 0.40                                   | 0.35 | 0.32 |    |    |
|                                                                                                                                           |                                                                                     | 8           | 0.48        | 0.39 | 0.33        | 0.47        | 0.38 | 0.33      | 0.37      | 0.32 | 0.29                                   | 0.36                                   | 0.32 | 0.29 |    |    |
|                                                                                                                                           |                                                                                     | 9           | 0.45        | 0.36 | 0.30        | 0.44        | 0.35 | 0.30      | 0.35      | 0.30 | 0.26                                   | 0.34                                   | 0.29 | 0.26 |    |    |
| 10                                                                                                                                        | 0.42                                                                                | 0.33        | 0.28        | 0.41 | 0.33        | 0.28        | 0.32 | 0.27      | 0.24      | 0.31 | 0.27                                   | 0.24                                   |      |      |    |    |
| <br>2 × 2, 3-Lamp troffer with A12 lens                |  | EFF = 68.4% |             |      | % DN = 100  |             |      | % UP = 0  |           |      | Lamp = (3) FT40<br>SC (along, across)  |                                        |      |      |    |    |
|                                                                                                                                           |                                                                                     | 0           | 0.81        | 0.81 | 0.81        | 0.80        | 0.80 | 0.80      | 0.76      | 0.76 | 0.76                                   | 0.73                                   | 0.73 | 0.73 |    |    |
|                                                                                                                                           |                                                                                     | 1           | 0.75        | 0.72 | 0.70        | 0.73        | 0.71 | 0.69      | 0.68      | 0.66 | 0.64                                   | 0.65                                   | 0.64 | 0.62 |    |    |
|                                                                                                                                           |                                                                                     | 2           | 0.69        | 0.64 | 0.60        | 0.68        | 0.63 | 0.59      | 0.61      | 0.58 | 0.55                                   | 0.59                                   | 0.56 | 0.54 |    |    |
|                                                                                                                                           |                                                                                     | 3           | 0.64        | 0.57 | 0.52        | 0.62        | 0.56 | 0.52      | 0.54      | 0.50 | 0.47                                   | 0.53                                   | 0.49 | 0.46 |    |    |
|                                                                                                                                           |                                                                                     | 4           | 0.59        | 0.52 | 0.46        | 0.58        | 0.51 | 0.46      | 0.49      | 0.45 | 0.41                                   | 0.47                                   | 0.44 | 0.41 |    |    |
|                                                                                                                                           |                                                                                     | 5           | 0.55        | 0.47 | 0.41        | 0.53        | 0.46 | 0.41      | 0.44      | 0.40 | 0.36                                   | 0.43                                   | 0.39 | 0.36 |    |    |
|                                                                                                                                           |                                                                                     | 6           | 0.51        | 0.42 | 0.37        | 0.49        | 0.42 | 0.36      | 0.40      | 0.36 | 0.32                                   | 0.39                                   | 0.35 | 0.32 |    |    |
|                                                                                                                                           |                                                                                     | 7           | 0.47        | 0.39 | 0.33        | 0.46        | 0.38 | 0.33      | 0.37      | 0.32 | 0.29                                   | 0.36                                   | 0.32 | 0.29 |    |    |
|                                                                                                                                           |                                                                                     | 8           | 0.44        | 0.35 | 0.30        | 0.43        | 0.35 | 0.30      | 0.34      | 0.29 | 0.26                                   | 0.33                                   | 0.29 | 0.26 |    |    |
|                                                                                                                                           |                                                                                     | 9           | 0.41        | 0.33 | 0.27        | 0.40        | 0.32 | 0.27      | 0.31      | 0.27 | 0.24                                   | 0.31                                   | 0.27 | 0.24 |    |    |

| lens | 10                                                                                                                                                                                                  | 0.39        | 0.30 | 0.25 | 0.38       | 0.30 | 0.25 | 0.29     | 0.25 | 0.22 | 0.29 | 0.24 | 0.21 |                                        |  |  |  |  |  |  |  |  |  |  |  |  |
|------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|------|------|------------|------|------|----------|------|------|------|------|------|----------------------------------------|--|--|--|--|--|--|--|--|--|--|--|--|
| 35   | <div><div></div><div></div></div> |             |      |      |            |      |      |          |      |      |      |      |      | Lamp = (2) F31T8<br>SC (along, across) |  |  |  |  |  |  |  |  |  |  |  |  |
|      |                                                                                                                                                                                                     | EFF = 57.1% |      |      | % DN = 100 |      |      | % UP = 0 |      |      |      |      |      |                                        |  |  |  |  |  |  |  |  |  |  |  |  |
|      | 0                                                                                                                                                                                                   | 0.68        | 0.68 | 0.68 | 0.66       | 0.66 | 0.66 | 0.63     | 0.63 | 0.63 | 0.61 | 0.61 | 0.61 |                                        |  |  |  |  |  |  |  |  |  |  |  |  |
|      | 1                                                                                                                                                                                                   | 0.64        | 0.62 | 0.60 | 0.62       | 0.60 | 0.59 | 0.58     | 0.57 | 0.55 | 0.56 | 0.55 | 0.54 |                                        |  |  |  |  |  |  |  |  |  |  |  |  |
|      | 2                                                                                                                                                                                                   | 0.59        | 0.55 | 0.52 | 0.58       | 0.54 | 0.51 | 0.52     | 0.50 | 0.48 | 0.51 | 0.49 | 0.47 |                                        |  |  |  |  |  |  |  |  |  |  |  |  |
|      | 3                                                                                                                                                                                                   | 0.55        | 0.50 | 0.46 | 0.53       | 0.49 | 0.45 | 0.47     | 0.44 | 0.42 | 0.46 | 0.43 | 0.41 |                                        |  |  |  |  |  |  |  |  |  |  |  |  |
|      | 4                                                                                                                                                                                                   | 0.51        | 0.45 | 0.40 | 0.49       | 0.44 | 0.40 | 0.43     | 0.39 | 0.36 | 0.41 | 0.38 | 0.36 |                                        |  |  |  |  |  |  |  |  |  |  |  |  |
|      | 5                                                                                                                                                                                                   | 0.47        | 0.40 | 0.36 | 0.46       | 0.40 | 0.36 | 0.39     | 0.35 | 0.32 | 0.38 | 0.34 | 0.32 |                                        |  |  |  |  |  |  |  |  |  |  |  |  |
|      | 6                                                                                                                                                                                                   | 0.43        | 0.37 | 0.32 | 0.42       | 0.36 | 0.32 | 0.35     | 0.31 | 0.28 | 0.34 | 0.31 | 0.28 |                                        |  |  |  |  |  |  |  |  |  |  |  |  |
|      | 7                                                                                                                                                                                                   | 0.40        | 0.33 | 0.29 | 0.39       | 0.33 | 0.29 | 0.32     | 0.28 | 0.25 | 0.31 | 0.28 | 0.25 |                                        |  |  |  |  |  |  |  |  |  |  |  |  |
|      | 8                                                                                                                                                                                                   | 0.38        | 0.31 | 0.26 | 0.37       | 0.30 | 0.26 | 0.29     | 0.26 | 0.23 | 0.29 | 0.25 | 0.23 |                                        |  |  |  |  |  |  |  |  |  |  |  |  |
|      | 9                                                                                                                                                                                                   | 0.35        | 0.28 | 0.24 | 0.34       | 0.28 | 0.24 | 0.27     | 0.23 | 0.21 | 0.27 | 0.23 | 0.21 |                                        |  |  |  |  |  |  |  |  |  |  |  |  |
|      | 10                                                                                                                                                                                                  | 0.33        | 0.26 | 0.22 | 0.32       | 0.26 | 0.22 | 0.25     | 0.21 | 0.19 | 0.25 | 0.21 | 0.19 |                                        |  |  |  |  |  |  |  |  |  |  |  |  |

**Figure 9-28 Continued**

| Typical Luminaire | Typical Intensity Distribution                                                      | $\rho_{cc} \rightarrow$                                                             | 80                                                   |                                                                                                                                                                                                    |                                                                                                                                                                                                    | 70                                                                                                                                                                                                 |                                                                                                                                                                                                    |    | 50 |    |    | 30                                          |                                             |    |  |
|-------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|----|----|----|---------------------------------------------|---------------------------------------------|----|--|
|                   |                                                                                     | $\rho_w \rightarrow$                                                                | 70                                                   | 50                                                                                                                                                                                                 | 30                                                                                                                                                                                                 | 70                                                                                                                                                                                                 | 50                                                                                                                                                                                                 | 30 | 50 | 30 | 10 | 50                                          | 30                                          | 10 |  |
|                   |                                                                                     | RCR<br>↓                                                                            | EFF = 65.1%      % DN = 100%      % UP = 0%          |                                                                                                                                                                                                    |                                                                                                                                                                                                    |                                                                                                                                                                                                    |                                                                                                                                                                                                    |    |    |    |    | Lamp = (2) F32T8<br>SC (along, across, ...) |                                             |    |  |
| 36                |   |   | 0<br>1<br>2<br>3<br>4<br>5<br>6<br>7<br>8<br>9<br>10 | 0.77 0.77 0.77<br>0.71 0.69 0.66<br>0.66 0.61 0.57<br>0.60 0.54 0.49<br>0.55 0.48 0.43<br>0.51 0.43 0.38<br>0.47 0.39 0.34<br>0.44 0.36 0.30<br>0.41 0.33 0.27<br>0.39 0.30 0.25<br>0.36 0.28 0.23 | 0.76 0.76 0.76<br>0.70 0.67 0.65<br>0.64 0.59 0.56<br>0.59 0.53 0.48<br>0.54 0.47 0.42<br>0.50 0.43 0.37<br>0.46 0.39 0.33<br>0.43 0.35 0.30<br>0.40 0.32 0.27<br>0.38 0.30 0.25<br>0.35 0.28 0.23 | 0.72 0.72 0.72<br>0.64 0.62 0.61<br>0.57 0.54 0.51<br>0.51 0.47 0.44<br>0.46 0.41 0.38<br>0.41 0.37 0.33<br>0.38 0.33 0.29<br>0.34 0.30 0.26<br>0.31 0.27 0.24<br>0.29 0.25 0.21<br>0.27 0.23 0.19 | 0.69 0.69 0.69<br>0.62 0.60 0.59<br>0.55 0.52 0.50<br>0.49 0.46 0.43<br>0.44 0.40 0.37<br>0.40 0.36 0.33<br>0.36 0.32 0.29<br>0.33 0.29 0.26<br>0.31 0.27 0.23<br>0.28 0.24 0.21<br>0.26 0.22 0.19 |    |    |    |    |                                             |                                             |    |  |
| 37                |  |  |                                                      | EFF = 68.9%      % DN = 91.4%      % UP = 8.6%                                                                                                                                                     |                                                                                                                                                                                                    |                                                                                                                                                                                                    |                                                                                                                                                                                                    |    |    |    |    |                                             | Lamp = (2) F32T8<br>SC (along, across, ...) |    |  |
|                   |                                                                                     |                                                                                     | 0<br>1<br>2<br>3<br>4<br>5<br>6<br>7<br>8<br>9<br>10 | 0.81 0.81 0.81<br>0.74 0.71 0.68<br>0.68 0.62 0.58<br>0.62 0.55 0.50<br>0.57 0.50 0.44<br>0.53 0.45 0.39<br>0.49 0.40 0.35<br>0.46 0.37 0.31<br>0.42 0.34 0.28<br>0.40 0.31 0.26<br>0.37 0.29 0.23 | 0.78 0.78 0.78<br>0.71 0.68 0.66<br>0.65 0.61 0.56<br>0.60 0.54 0.49<br>0.55 0.48 0.43<br>0.51 0.43 0.38<br>0.47 0.39 0.34<br>0.44 0.36 0.31<br>0.41 0.33 0.28<br>0.38 0.30 0.25<br>0.36 0.28 0.23 | 0.73 0.73 0.73<br>0.64 0.62 0.60<br>0.57 0.54 0.51<br>0.51 0.47 0.44<br>0.46 0.41 0.38<br>0.41 0.37 0.33<br>0.38 0.33 0.29<br>0.34 0.30 0.26<br>0.32 0.27 0.23<br>0.29 0.24 0.21<br>0.27 0.22 0.19 | 0.69 0.69 0.69<br>0.61 0.59 0.58<br>0.54 0.51 0.49<br>0.48 0.45 0.42<br>0.44 0.40 0.37<br>0.39 0.35 0.32<br>0.36 0.32 0.29<br>0.33 0.29 0.26<br>0.30 0.26 0.23<br>0.20 0.24 0.21<br>0.26 0.22 0.19 |    |    |    |    |                                             |                                             |    |  |
| 38                |  |  |                                                      | EFF = 54.2%      % DN = 99.2%      % UP = 0.5%                                                                                                                                                     |                                                                                                                                                                                                    |                                                                                                                                                                                                    |                                                                                                                                                                                                    |    |    |    |    |                                             | Lamp = (2) FT36*<br>SC (along, across, ...) |    |  |
|                   |                                                                                     |                                                                                     | 0<br>1<br>2<br>3<br>4<br>5<br>6<br>7<br>8<br>9<br>10 | 0.65 0.65 0.65<br>0.58 0.55 0.53<br>0.53 0.48 0.44<br>0.48 0.42 0.37<br>0.43 0.37 0.32<br>0.40 0.33 0.27<br>0.37 0.29 0.24<br>0.34 0.26 0.21<br>0.32 0.24 0.19<br>0.29 0.22 0.17<br>0.28 0.20 0.16 | 0.63 0.63 0.63<br>0.57 0.54 0.52<br>0.51 0.47 0.43<br>0.46 0.41 0.36<br>0.42 0.36 0.31<br>0.39 0.32 0.27<br>0.36 0.29 0.24<br>0.33 0.26 0.21<br>0.31 0.24 0.19<br>0.29 0.22 0.17<br>0.27 0.20 0.16 | 0.60 0.60 0.60<br>0.52 0.50 0.48<br>0.45 0.41 0.39<br>0.39 0.35 0.32<br>0.34 0.30 0.27<br>0.31 0.26 0.23<br>0.28 0.23 0.20<br>0.25 0.21 0.18<br>0.23 0.19 0.16<br>0.21 0.17 0.14<br>0.19 0.15 0.13 | 0.58 0.58 0.58<br>0.49 0.48 0.46<br>0.43 0.40 0.38<br>0.37 0.34 0.31<br>0.33 0.29 0.27<br>0.30 0.26 0.23<br>0.27 0.23 0.20<br>0.24 0.20 0.18<br>0.22 0.18 0.16<br>0.20 0.17 0.14<br>0.19 0.15 0.13 |    |    |    |    |                                             |                                             |    |  |
| 39                |  |  |                                                      | EFF = 84.1%      % DN = 0      % UP = 100                                                                                                                                                          |                                                                                                                                                                                                    |                                                                                                                                                                                                    |                                                                                                                                                                                                    |    |    |    |    |                                             | Lamp = (2) F32T8<br>SC (along, across, ...) |    |  |
|                   |                                                                                     |                                                                                     | 0<br>1<br>2<br>3<br>4<br>5<br>6<br>7                 | 0.80 0.80 0.80<br>0.73 0.69 0.66<br>0.66 0.61 0.56<br>0.60 0.53 0.48<br>0.55 0.47 0.41<br>0.50 0.41 0.35<br>0.46 0.37 0.31<br>0.42 0.33 0.27                                                       | 0.68 0.68 0.68<br>0.62 0.59 0.57<br>0.56 0.52 0.48<br>0.51 0.46 0.41<br>0.47 0.40 0.35<br>0.43 0.36 0.30<br>0.39 0.32 0.27<br>0.36 0.28 0.23                                                       | 0.47 0.47 0.47<br>0.41 0.39 0.38<br>0.36 0.33 0.31<br>0.31 0.28 0.26<br>0.28 0.25 0.22<br>0.24 0.21 0.19<br>0.22 0.19 0.16<br>0.20 0.16 0.14                                                       | 0.27 0.27 0.27<br>0.23 0.23 0.22<br>0.21 0.19 0.18<br>0.18 0.17 0.15<br>0.16 0.14 0.13<br>0.14 0.12 0.11<br>0.13 0.11 0.10<br>0.11 0.10 0.09                                                       |    |    |    |    |                                             |                                             |    |  |

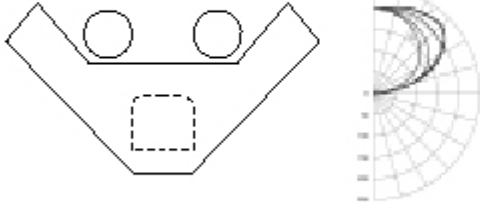
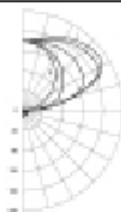
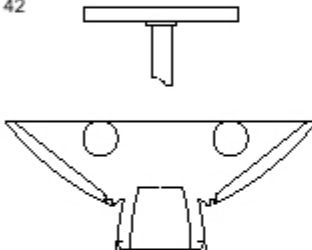
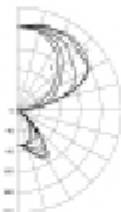
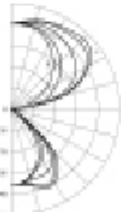
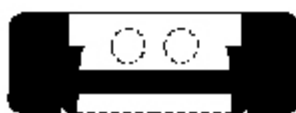
|                                                                                                                          |                                                                                    |      |      |      |      |      |      |      |      |      |      |      |      |
|--------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|------|------|------|------|------|------|------|------|------|------|------|------|
| 9" Wide, thin profile, wide spread indirect                                                                              | 8                                                                                  | 0.39 | 0.30 | 0.24 | 0.33 | 0.26 | 0.21 | 0.18 | 0.14 | 0.12 | 0.10 | 0.09 | 0.07 |
|                                                                                                                          | 9                                                                                  | 0.36 | 0.27 | 0.21 | 0.31 | 0.23 | 0.18 | 0.16 | 0.13 | 0.11 | 0.09 | 0.08 | 0.06 |
|                                                                                                                          | 10                                                                                 | 0.34 | 0.24 | 0.19 | 0.29 | 0.21 | 0.16 | 0.15 | 0.11 | 0.09 | 0.08 | 0.07 | 0.06 |
| 40<br><br>V-shaped, completely indirect | EFF = 88.3%      % DN = 0      % UP = 100      Lamp = (2) F32T8 SC (along, across) |      |      |      |      |      |      |      |      |      |      |      |      |
|                                                                                                                          | 0                                                                                  | 0.84 | 0.84 | 0.84 | 0.72 | 0.72 | 0.72 | 0.49 | 0.49 | 0.49 | 0.28 | 0.28 | 0.28 |
|                                                                                                                          | 1                                                                                  | 0.76 | 0.73 | 0.70 | 0.65 | 0.62 | 0.60 | 0.43 | 0.41 | 0.40 | 0.25 | 0.24 | 0.23 |
|                                                                                                                          | 2                                                                                  | 0.70 | 0.64 | 0.59 | 0.59 | 0.54 | 0.50 | 0.37 | 0.35 | 0.33 | 0.22 | 0.20 | 0.19 |
|                                                                                                                          | 3                                                                                  | 0.63 | 0.56 | 0.50 | 0.54 | 0.48 | 0.43 | 0.33 | 0.30 | 0.27 | 0.19 | 0.17 | 0.16 |
|                                                                                                                          | 4                                                                                  | 0.58 | 0.49 | 0.43 | 0.49 | 0.42 | 0.37 | 0.29 | 0.26 | 0.23 | 0.17 | 0.15 | 0.14 |
|                                                                                                                          | 5                                                                                  | 0.53 | 0.43 | 0.37 | 0.45 | 0.37 | 0.32 | 0.26 | 0.22 | 0.20 | 0.15 | 0.13 | 0.12 |
|                                                                                                                          | 6                                                                                  | 0.48 | 0.39 | 0.32 | 0.41 | 0.33 | 0.28 | 0.23 | 0.19 | 0.17 | 0.13 | 0.11 | 0.10 |
|                                                                                                                          | 7                                                                                  | 0.45 | 0.35 | 0.28 | 0.38 | 0.30 | 0.24 | 0.21 | 0.17 | 0.15 | 0.12 | 0.10 | 0.09 |
|                                                                                                                          | 8                                                                                  | 0.41 | 0.31 | 0.25 | 0.35 | 0.27 | 0.22 | 0.19 | 0.15 | 0.13 | 0.11 | 0.09 | 0.08 |
|                                                                                                                          | 9                                                                                  | 0.38 | 0.28 | 0.22 | 0.32 | 0.24 | 0.19 | 0.17 | 0.13 | 0.11 | 0.10 | 0.08 | 0.07 |
|                                                                                                                          | 10                                                                                 | 0.35 | 0.26 | 0.20 | 0.30 | 0.22 | 0.17 | 0.15 | 0.12 | 0.10 | 0.09 | 0.07 | 0.06 |

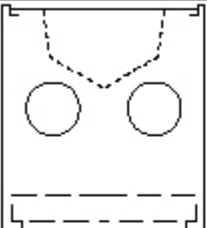
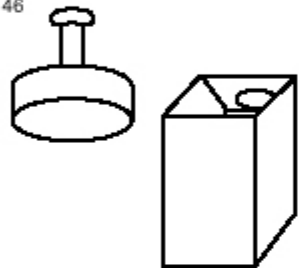
Figure 9-28 Continued

| Typical Luminaire                                                                                                                                     | Typical Intensity Distribution                                                      | $\rho_{cc} \rightarrow$                                                                 | 80                                             |      |      | 70   |      |      | 50   |      |      | 30                                 |      |     |
|-------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------|------------------------------------------------|------|------|------|------|------|------|------|------|------------------------------------|------|-----|
|                                                                                                                                                       |                                                                                     | $\rho_w \rightarrow$                                                                    | 70                                             | 50   | 30   | 70   | 50   | 30   | 50   | 30   | 10   | 50                                 | 30   | 10  |
|                                                                                                                                                       |                                                                                     | RCR<br>$\downarrow$                                                                     | EFF = 82.4%      % DN = 5.4%      % UP = 94.6% |      |      |      |      |      |      |      |      | Lamp = (2) F32T SC (along, across) |      |     |
| <br>Indirect with perforated metal underside                        |   | 0                                                                                       | 0.80                                           | 0.80 | 0.80 | 0.69 | 0.69 | 0.69 | 0.48 | 0.48 | 0.48 | 0.30                               | 0.30 | 0.3 |
|                                                                                                                                                       |                                                                                     | 1                                                                                       | 0.72                                           | 0.69 | 0.66 | 0.62 | 0.59 | 0.57 | 0.42 | 0.40 | 0.39 | 0.27                               | 0.25 | 0.2 |
|                                                                                                                                                       |                                                                                     | 2                                                                                       | 0.66                                           | 0.60 | 0.55 | 0.56 | 0.52 | 0.48 | 0.37 | 0.34 | 0.32 | 0.22                               | 0.21 | 0.2 |
|                                                                                                                                                       |                                                                                     | 3                                                                                       | 0.60                                           | 0.53 | 0.47 | 0.51 | 0.45 | 0.41 | 0.32 | 0.29 | 0.27 | 0.20                               | 0.18 | 0.1 |
|                                                                                                                                                       |                                                                                     | 4                                                                                       | 0.55                                           | 0.46 | 0.40 | 0.47 | 0.40 | 0.35 | 0.28 | 0.25 | 0.23 | 0.17                               | 0.16 | 0.1 |
|                                                                                                                                                       |                                                                                     | 5                                                                                       | 0.50                                           | 0.41 | 0.35 | 0.43 | 0.36 | 0.30 | 0.25 | 0.22 | 0.19 | 0.16                               | 0.14 | 0.1 |
|                                                                                                                                                       |                                                                                     | 6                                                                                       | 0.46                                           | 0.37 | 0.30 | 0.39 | 0.32 | 0.27 | 0.23 | 0.19 | 0.17 | 0.14                               | 0.12 | 0.1 |
|                                                                                                                                                       |                                                                                     | 7                                                                                       | 0.42                                           | 0.33 | 0.27 | 0.36 | 0.28 | 0.23 | 0.20 | 0.17 | 0.14 | 0.13                               | 0.11 | 0.0 |
|                                                                                                                                                       |                                                                                     | 8                                                                                       | 0.39                                           | 0.29 | 0.24 | 0.33 | 0.26 | 0.21 | 0.18 | 0.15 | 0.13 | 0.11                               | 0.09 | 0.0 |
|                                                                                                                                                       |                                                                                     | 9                                                                                       | 0.36                                           | 0.27 | 0.21 | 0.31 | 0.23 | 0.18 | 0.17 | 0.13 | 0.11 | 0.10                               | 0.08 | 0.0 |
|                                                                                                                                                       |                                                                                     | 10                                                                                      | 0.33                                           | 0.24 | 0.19 | 0.29 | 0.21 | 0.16 | 0.15 | 0.12 | 0.10 | 0.05                               | 0.08 | 0.0 |
| <br>Semi-indirect, 2-lamp, v-shape, parabolic baffles              |  | EFF = 83.2%      % DN = 21.6%      % UP = 78.4%      Lamp = (2) F32T SC (along, across) |                                                |      |      |      |      |      |      |      |      |                                    |      |     |
|                                                                                                                                                       |                                                                                     | 0                                                                                       | 0.83                                           | 0.83 | 0.83 | 0.74 | 0.74 | 0.74 | 0.56 | 0.56 | 0.56 | 0.39                               | 0.39 | 0.3 |
|                                                                                                                                                       |                                                                                     | 1                                                                                       | 0.76                                           | 0.73 | 0.70 | 0.67 | 0.65 | 0.62 | 0.49 | 0.48 | 0.46 | 0.35                               | 0.34 | 0.3 |
|                                                                                                                                                       |                                                                                     | 2                                                                                       | 0.70                                           | 0.64 | 0.59 | 0.62 | 0.57 | 0.53 | 0.44 | 0.41 | 0.39 | 0.31                               | 0.30 | 0.2 |
|                                                                                                                                                       |                                                                                     | 3                                                                                       | 0.64                                           | 0.57 | 0.51 | 0.56 | 0.50 | 0.46 | 0.39 | 0.36 | 0.33 | 0.28                               | 0.26 | 0.2 |
|                                                                                                                                                       |                                                                                     | 4                                                                                       | 0.58                                           | 0.50 | 0.44 | 0.52 | 0.45 | 0.40 | 0.35 | 0.31 | 0.28 | 0.25                               | 0.23 | 0.2 |
|                                                                                                                                                       |                                                                                     | 5                                                                                       | 0.54                                           | 0.45 | 0.39 | 0.47 | 0.40 | 0.35 | 0.31 | 0.27 | 0.25 | 0.23                               | 0.20 | 0.1 |
|                                                                                                                                                       |                                                                                     | 6                                                                                       | 0.49                                           | 0.40 | 0.34 | 0.44 | 0.36 | 0.31 | 0.28 | 0.24 | 0.21 | 0.20                               | 0.18 | 0.1 |
|                                                                                                                                                       |                                                                                     | 7                                                                                       | 0.46                                           | 0.36 | 0.30 | 0.40 | 0.32 | 0.27 | 0.25 | 0.22 | 0.19 | 0.19                               | 0.16 | 0.1 |
|                                                                                                                                                       |                                                                                     | 8                                                                                       | 0.42                                           | 0.33 | 0.27 | 0.37 | 0.29 | 0.24 | 0.23 | 0.19 | 0.17 | 0.17                               | 0.15 | 0.1 |
|                                                                                                                                                       |                                                                                     | 9                                                                                       | 0.39                                           | 0.30 | 0.24 | 0.35 | 0.27 | 0.22 | 0.21 | 0.17 | 0.15 | 0.16                               | 0.13 | 0.1 |
|                                                                                                                                                       |                                                                                     | 10                                                                                      | 0.37                                           | 0.27 | 0.22 | 0.32 | 0.24 | 0.20 | 0.19 | 0.16 | 0.13 | 0.14                               | 0.12 | 0.1 |
| <br>Semi-indirect, 2-lamp, thin profile, parabolic baffles, 70% up |  | EFF = 85.2%      % DN = 28.7%      % UP = 71.3%      Lamp = (2) F32T SC (along, across) |                                                |      |      |      |      |      |      |      |      |                                    |      |     |
|                                                                                                                                                       |                                                                                     | 0                                                                                       | 3.87                                           | 0.87 | 0.87 | 0.78 | 0.78 | 0.78 | 0.61 | 0.61 | 0.61 | 0.45                               | 0.45 | 0.4 |
|                                                                                                                                                       |                                                                                     | 1                                                                                       | 3.80                                           | 0.77 | 0.74 | 0.72 | 0.69 | 0.66 | 0.54 | 0.53 | 0.51 | 0.41                               | 0.40 | 0.3 |
|                                                                                                                                                       |                                                                                     | 2                                                                                       | 0.73                                           | 0.68 | 0.63 | 0.66 | 0.61 | 0.57 | 0.48 | 0.46 | 0.44 | 0.37                               | 0.35 | 0.3 |
|                                                                                                                                                       |                                                                                     | 3                                                                                       | 0.67                                           | 0.60 | 0.55 | 0.60 | 0.54 | 0.50 | 0.43 | 0.40 | 0.37 | 0.33                               | 0.31 | 0.2 |
|                                                                                                                                                       |                                                                                     | 4                                                                                       | 0.62                                           | 0.54 | 0.48 | 0.55 | 0.49 | 0.43 | 0.39 | 0.35 | 0.32 | 0.30                               | 0.28 | 0.2 |
|                                                                                                                                                       |                                                                                     | 5                                                                                       | 0.57                                           | 0.48 | 0.42 | 0.51 | 0.44 | 0.38 | 0.35 | 0.31 | 0.28 | 0.27                               | 0.25 | 0.2 |
|                                                                                                                                                       |                                                                                     | 6                                                                                       | 0.53                                           | 0.43 | 0.37 | 0.47 | 0.39 | 0.34 | 0.32 | 0.28 | 0.25 | 0.25                               | 0.22 | 0.2 |
|                                                                                                                                                       |                                                                                     | 7                                                                                       | 0.49                                           | 0.39 | 0.33 | 0.44 | 0.36 | 0.30 | 0.29 | 0.25 | 0.22 | 0.23                               | 0.20 | 0.1 |
|                                                                                                                                                       |                                                                                     | 8                                                                                       | 0.45                                           | 0.35 | 0.29 | 0.41 | 0.32 | 0.27 | 0.26 | 0.22 | 0.20 | 0.21                               | 0.18 | 0.1 |
|                                                                                                                                                       |                                                                                     | 9                                                                                       | 0.42                                           | 0.32 | 0.26 | 0.38 | 0.30 | 0.24 | 0.24 | 0.20 | 0.18 | 0.19                               | 0.16 | 0.1 |
|                                                                                                                                                       |                                                                                     | 10                                                                                      | 0.39                                           | 0.30 | 0.24 | 0.35 | 0.27 | 0.22 | 0.22 | 0.18 | 0.16 | 0.18                               | 0.15 | 0.1 |
|                                                                    |  | EFF = 88.3%      % DN = 40.3      % UP = 59.7      Lamp = (2) F32T SC (along, across)   |                                                |      |      |      |      |      |      |      |      |                                    |      |     |
|                                                                                                                                                       |                                                                                     | 0                                                                                       | 0.93                                           | 0.93 | 0.93 | 0.84 | 0.84 | 0.84 | 0.69 | 0.69 | 0.69 | 0.55                               | 0.55 | 0.5 |
|                                                                                                                                                       |                                                                                     | 1                                                                                       | 0.85                                           | 0.82 | 0.79 | 0.77 | 0.75 | 0.72 | 0.61 | 0.60 | 0.58 | 0.49                               | 0.48 | 0.4 |
|                                                                                                                                                       |                                                                                     | 2                                                                                       | 0.78                                           | 0.72 | 0.67 | 0.71 | 0.66 | 0.62 | 0.54 | 0.51 | 0.49 | 0.44                               | 0.42 | 0.4 |
|                                                                                                                                                       |                                                                                     | 3                                                                                       | 0.71                                           | 0.64 | 0.58 | 0.65 | 0.58 | 0.53 | 0.48 | 0.45 | 0.42 | 0.39                               | 0.37 | 0.3 |
|                                                                                                                                                       |                                                                                     | 4                                                                                       | 0.65                                           | 0.57 | 0.50 | 0.60 | 0.52 | 0.46 | 0.43 | 0.39 | 0.36 | 0.35                               | 0.32 | 0.3 |



|                                                                  |                                                                                   |    |      |      |      |      |      |      |      |      |      |      |      |     |
|------------------------------------------------------------------|-----------------------------------------------------------------------------------|----|------|------|------|------|------|------|------|------|------|------|------|-----|
| Direct/indirect, 2-lamp, thin profile, parabolic baffles, 60% up |  | 6  | 0.55 | 0.45 | 0.38 | 0.50 | 0.42 | 0.36 | 0.35 | 0.30 | 0.27 | 0.28 | 0.25 | 0.2 |
|                                                                  |                                                                                   | 7  | 0.51 | 0.41 | 0.34 | 0.47 | 0.38 | 0.32 | 0.32 | 0.27 | 0.24 | 0.26 | 0.23 | 0.2 |
|                                                                  |                                                                                   | 8  | 0.47 | 0.37 | 0.30 | 0.43 | 0.34 | 0.28 | 0.29 | 0.24 | 0.21 | 0.24 | 0.20 | 0.1 |
|                                                                  |                                                                                   | 9  | 0.44 | 0.34 | 0.27 | 0.40 | 0.31 | 0.25 | 0.26 | 0.22 | 0.19 | 0.22 | 0.18 | 0.1 |
|                                                                  |                                                                                   | 10 | 0.41 | 0.31 | 0.25 | 0.37 | 0.28 | 0.23 | 0.24 | 0.20 | 0.17 | 0.20 | 0.17 | 0.1 |

Figure 9-28 Continued

| Typical Luminaire                                                                                                               | Typical Intensity Distribution | $\rho_{cc} \rightarrow$ | 80          |             |      | 70           |              |      | 50           |                                        |      | 30                                     |                    |    |  |
|---------------------------------------------------------------------------------------------------------------------------------|--------------------------------|-------------------------|-------------|-------------|------|--------------|--------------|------|--------------|----------------------------------------|------|----------------------------------------|--------------------|----|--|
|                                                                                                                                 |                                | $\rho_w \rightarrow$    | 70          | 50          | 30   | 70           | 50           | 30   | 50           | 30                                     | 10   | 50                                     | 30                 | 10 |  |
|                                                                                                                                 |                                | RCR<br>↓                | EFF = 53.4% |             |      | % DN = 81.7% |              |      | % UP = 18.3% |                                        |      | Lamp = (2) F32T8<br>SC (along, across) |                    |    |  |
| <br>6" square x-section, mostly downlight      | 0                              | 0.61                    | 0.61        | 0.61        | 0.59 | 0.59         | 0.59         | 0.54 | 0.54         | 0.54                                   | 0.50 | 0.50                                   | 0.50               |    |  |
|                                                                                                                                 | 1                              | 0.57                    | 0.55        | 0.53        | 0.55 | 0.53         | 0.51         | 0.49 | 0.48         | 0.47                                   | 0.45 | 0.44                                   | 0.44               |    |  |
|                                                                                                                                 | 2                              | 0.53                    | 0.49        | 0.46        | 0.51 | 0.48         | 0.45         | 0.44 | 0.42         | 0.40                                   | 0.41 | 0.39                                   | 0.36               |    |  |
|                                                                                                                                 | 3                              | 0.49                    | 0.44        | 0.41        | 0.47 | 0.43         | 0.39         | 0.40 | 0.37         | 0.35                                   | 0.37 | 0.35                                   | 0.33               |    |  |
|                                                                                                                                 | 4                              | 0.45                    | 0.40        | 0.36        | 0.43 | 0.38         | 0.35         | 0.36 | 0.33         | 0.31                                   | 0.34 | 0.31                                   | 0.29               |    |  |
|                                                                                                                                 | 5                              | 0.42                    | 0.36        | 0.32        | 0.40 | 0.35         | 0.31         | 0.33 | 0.30         | 0.27                                   | 0.31 | 0.28                                   | 0.26               |    |  |
|                                                                                                                                 | 6                              | 0.39                    | 0.33        | 0.29        | 0.37 | 0.32         | 0.28         | 0.30 | 0.27         | 0.24                                   | 0.28 | 0.25                                   | 0.23               |    |  |
|                                                                                                                                 | 7                              | 0.36                    | 0.30        | 0.26        | 0.35 | 0.29         | 0.25         | 0.27 | 0.24         | 0.22                                   | 0.26 | 0.23                                   | 0.21               |    |  |
|                                                                                                                                 | 8                              | 0.34                    | 0.27        | 0.23        | 0.32 | 0.27         | 0.23         | 0.25 | 0.22         | 0.19                                   | 0.24 | 0.21                                   | 0.19               |    |  |
|                                                                                                                                 | 9                              | 0.32                    | 0.25        | 0.21        | 0.30 | 0.24         | 0.21         | 0.23 | 0.20         | 0.18                                   | 0.22 | 0.19                                   | 0.17               |    |  |
|                                                                                                                                 | 10                             | 0.30                    | 0.23        | 0.19        | 0.29 | 0.23         | 0.19         | 0.21 | 0.18         | 0.16                                   | 0.20 | 0.18                                   | 0.16               |    |  |
| <br>Completely indirect HID                   | EFF = 73%                      |                         |             | % DN = 90%  |      |              | % UP = 100%  |      |              | Lamp = M400/U (                        |      |                                        | SC (along, across) |    |  |
|                                                                                                                                 | 0                              | 0.69                    | 0.69        | 0.69        | 0.59 | 0.59         | 0.59         | 0.41 | 0.54         | 0.41                                   | 0.23 | 0.23                                   | 0.23               |    |  |
|                                                                                                                                 | 1                              | 0.63                    | 0.60        | 0.58        | 0.54 | 0.52         | 0.43         | 0.35 | 0.34         | 0.33                                   | 0.20 | 0.20                                   | 0.19               |    |  |
|                                                                                                                                 | 2                              | 0.57                    | 0.53        | 0.48        | 0.49 | 0.45         | 0.42         | 0.31 | 0.29         | 0.27                                   | 0.18 | 0.17                                   | 0.16               |    |  |
|                                                                                                                                 | 3                              | 0.52                    | 0.46        | 0.41        | 0.45 | 0.39         | 0.36         | 0.27 | 0.25         | 0.23                                   | 0.16 | 0.14                                   | 0.13               |    |  |
|                                                                                                                                 | 4                              | 0.48                    | 0.41        | 0.35        | 0.41 | 0.35         | 0.31         | 0.24 | 0.21         | 0.19                                   | 0.14 | 0.12                                   | 0.11               |    |  |
|                                                                                                                                 | 5                              | 0.44                    | 0.36        | 0.31        | 0.37 | 0.31         | 0.26         | 0.21 | 0.18         | 0.16                                   | 0.12 | 0.11                                   | 0.10               |    |  |
|                                                                                                                                 | 6                              | 0.40                    | 0.32        | 0.27        | 0.34 | 0.27         | 0.23         | 0.19 | 0.16         | 0.14                                   | 0.11 | 0.09                                   | 0.08               |    |  |
|                                                                                                                                 | 7                              | 0.37                    | 0.29        | 0.23        | 0.31 | 0.25         | 0.20         | 0.17 | 0.14         | 0.12                                   | 0.10 | 0.08                                   | 0.07               |    |  |
|                                                                                                                                 | 8                              | 0.34                    | 0.26        | 0.21        | 0.29 | 0.22         | 0.18         | 0.15 | 0.13         | 0.11                                   | 0.09 | 0.07                                   | 0.06               |    |  |
|                                                                                                                                 | 9                              | 0.31                    | 0.23        | 0.18        | 0.27 | 0.20         | 0.16         | 0.14 | 0.11         | 0.09                                   | 0.08 | 0.07                                   | 0.05               |    |  |
|                                                                                                                                 | 10                             | 0.29                    | 0.21        | 0.16        | 0.25 | 0.18         | 0.14         | 0.13 | 0.10         | 0.08                                   | 0.07 | 0.06                                   | 0.05               |    |  |
| <br>Fluorescent cove with specular reflector | EFF = 71.6%                    |                         |             | % DN = 0.3% |      |              | % UP = 99.7% |      |              | Lamp = (1) F32T8<br>SC (along, across) |      |                                        |                    |    |  |
|                                                                                                                                 | 0                              | 0.42                    | 0.35        | 0.30        | 0.40 | 0.34         | 0.30         | 0.32 | 0.28         | 0.26                                   | 0.30 | 0.27                                   | 0.25               |    |  |
|                                                                                                                                 | 1                              | 0.40                    | 0.32        | 0.28        | 0.38 | 0.31         | 0.27         | 0.30 | 0.26         | 0.24                                   | 0.28 | 0.25                                   | 0.23               |    |  |
|                                                                                                                                 | 2                              | 0.37                    | 0.30        | 0.26        | 0.36 | 0.29         | 0.25         | 0.28 | 0.24         | 0.22                                   | 0.26 | 0.23                                   | 0.21               |    |  |
|                                                                                                                                 | 3                              | 0.35                    | 0.28        | 0.24        | 0.34 | 0.27         | 0.23         | 0.26 | 0.22         | 0.20                                   | 0.25 | 0.22                                   | 0.19               |    |  |
|                                                                                                                                 | 4                              | 0.00                    | 0.00        | 0.00        | 0.00 | 0.00         | 0.00         | 0.00 | 0.00         | 0.00                                   | 0.00 | 0.00                                   | 0.00               |    |  |
|                                                                                                                                 | 5                              | 0.00                    | 0.00        | 0.00        | 0.00 | 0.00         | 0.00         | 0.00 | 0.00         | 0.00                                   | 0.00 | 0.00                                   | 0.00               |    |  |
|                                                                                                                                 | 6                              | 0.67                    | 0.67        | 0.67        | 0.64 | 0.64         | 0.64         | 0.58 | 0.58         | 0.58                                   | 0.53 | 0.53                                   | 0.53               |    |  |
|                                                                                                                                 | 7                              | 0.62                    | 0.59        | 0.57        | 0.59 | 0.57         | 0.55         | 0.52 | 0.50         | 0.49                                   | 0.48 | 0.46                                   | 0.45               |    |  |
|                                                                                                                                 | 8                              | 0.57                    | 0.53        | 0.50        | 0.55 | 0.51         | 0.48         | 0.47 | 0.45         | 0.43                                   | 0.43 | 0.41                                   | 0.40               |    |  |
|                                                                                                                                 | 9                              | 0.53                    | 0.48        | 0.44        | 0.51 | 0.46         | 0.43         | 0.43 | 0.40         | 0.37                                   | 0.40 | 0.37                                   | 0.35               |    |  |
|                                                                                                                                 | 10                             | 0.50                    | 0.44        | 0.39        | 0.47 | 0.42         | 0.38         | 0.39 | 0.36         | 0.33                                   | 0.36 | 0.34                                   | 0.32               |    |  |

Notes: EFF = efficiency; SC = spacing criteria.

For 6" reflector with PAR-38, multiply by 0.98.

For A12 lens, 2 × 4's, ratio of F40 to T8, 0.96, 0.94, and 0.89 for 2, 3, and 4-lamp versions.

For A12 lens, 2 × 4's, ratio of 2 to 3-lamp eff. = 1.05; ratio of 4 to 3-lamp eff. = 0.98.

For parabolics, 2 lamp versions have 12 cells, 4 lamp versions have 32 cells.

For 3" parabolic, 2 × 4's, ratio of 2 to 3-lamp eff. = 1.06; ratio of 4 to 3-lamp eff. = 0.96.

For 4" parabolic, 2 × 4's, ratio of 2 to 3-lamp eff. = 0.98; ratio of 4 to 3-lamp eff. = 0.90.

CUs do not consider shadowing of the lighting fixture or cove.

\* Different lamp types have been considered in determining the listed photometric report.

Figure 9-28 Coefficients of Utilization for Typical Luminaires

## Average Exitance Calculations: The Lumen Method

Exitance calculations are greatly simplified through the use of exitance coefficients (ECs). These coefficients, like coefficients of utilization, may be computed for any luminaire, although they are somewhat rare in manufacturers' literature.



somewhat rare in manufacturers' literature.

Exitance coefficients are similar to coefficients of utilization, except that they apply to the surfaces of the room cavity. They may be substituted into a variation of the lumen method formula in place of the coefficient of utilization. The result obtained is either the average wall exitance or the average ceiling cavity exitance, rather than illuminance on the workplane. Thus

$$\begin{aligned} &\text{average initial wall exitance} \\ &= \text{total bare-lamp lumens} \\ &\quad \times \frac{\text{ceiling exitance coefficient}}{\text{floor area}} \end{aligned} \quad (9-59)$$

and

$$\begin{aligned} &\text{average initial ceiling cavity exitance} \\ &= \text{total bare-lamp lumens} \\ &\quad \times \frac{\text{ceiling cavity exitance coefficient}}{\text{floor area}} \end{aligned} \quad (9-60)$$

| % Effective Ceiling Cavity Reflectance, $\rho_{cc}$     | 80    |       |       |       | 70    |       |       |       | 50    |       |       |       | 30    |       |  |
|---------------------------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--|
|                                                         |       |       |       |       |       |       |       |       |       |       |       |       |       |       |  |
| % Wall Reflectance, $\rho_w$                            | 70    | 50    | 30    | 10    | 70    | 50    | 30    | 10    | 50    | 30    | 10    | 50    | 30    | 10    |  |
| For 30% Effective Floor Cavity Reflectance (20% = 1.00) |       |       |       |       |       |       |       |       |       |       |       |       |       |       |  |
| Room Cavity Ratio                                       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |  |
| 1                                                       | 1.092 | 1.082 | 1.075 | 1.068 | 1.077 | 1.070 | 1.064 | 1.059 | 1.049 | 1.044 | 1.040 | 1.028 | 1.026 | 1.023 |  |
| 2                                                       | 1.079 | 1.066 | 1.055 | 1.047 | 1.068 | 1.057 | 1.048 | 1.039 | 1.041 | 1.033 | 1.027 | 1.026 | 1.021 | 1.017 |  |
| 3                                                       | 1.070 | 1.054 | 1.042 | 1.033 | 1.061 | 1.048 | 1.037 | 1.028 | 1.034 | 1.027 | 1.020 | 1.024 | 1.017 | 1.012 |  |
| 4                                                       | 1.062 | 1.045 | 1.033 | 1.024 | 1.055 | 1.040 | 1.029 | 1.021 | 1.030 | 1.022 | 1.015 | 1.022 | 1.015 | 1.010 |  |
| 5                                                       | 1.056 | 1.038 | 1.026 | 1.018 | 1.050 | 1.034 | 1.024 | 1.015 | 1.027 | 1.018 | 1.012 | 1.020 | 1.013 | 1.008 |  |
| 6                                                       | 1.052 | 1.033 | 1.021 | 1.014 | 1.047 | 1.030 | 1.020 | 1.012 | 1.024 | 1.015 | 1.009 | 1.019 | 1.012 | 1.006 |  |
| 7                                                       | 1.047 | 1.029 | 1.018 | 1.011 | 1.043 | 1.026 | 1.017 | 1.009 | 1.022 | 1.013 | 1.007 | 1.018 | 1.010 | 1.005 |  |
| 8                                                       | 1.044 | 1.026 | 1.015 | 1.009 | 1.040 | 1.024 | 1.015 | 1.007 | 1.020 | 1.012 | 1.006 | 1.017 | 1.009 | 1.004 |  |
| 9                                                       | 1.040 | 1.024 | 1.014 | 1.007 | 1.037 | 1.022 | 1.014 | 1.006 | 1.019 | 1.011 | 1.005 | 1.016 | 1.009 | 1.004 |  |
| 10                                                      | 1.037 | 1.022 | 1.012 | 1.006 | 1.034 | 1.020 | 1.012 | 1.005 | 1.017 | 1.010 | 1.004 | 1.015 | 1.009 | 1.003 |  |
| For 10% Effective Floor Cavity Reflectance (20% = 1.00) |       |       |       |       |       |       |       |       |       |       |       |       |       |       |  |
| Room Cavity Ratio                                       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |  |
| 1                                                       | .923  | .929  | .935  | .940  | .933  | .939  | .943  | .948  | .956  | .960  | .963  | .973  | .976  | .979  |  |
| 2                                                       | .931  | .942  | .950  | .958  | .940  | .949  | .957  | .963  | .962  | .968  | .974  | .976  | .980  | .985  |  |
| 3                                                       | .939  | .951  | .961  | .969  | .945  | .957  | .966  | .973  | .967  | .975  | .981  | .978  | .983  | .988  |  |
| 4                                                       | .944  | .958  | .969  | .978  | .950  | .963  | .973  | .980  | .972  | .980  | .986  | .980  | .986  | .991  |  |
| 5                                                       | .949  | .964  | .976  | .983  | .954  | .968  | .978  | .985  | .975  | .983  | .989  | .981  | .988  | .993  |  |
| 6                                                       | .953  | .969  | .980  | .986  | .958  | .972  | .982  | .989  | .977  | .985  | .992  | .982  | .989  | .995  |  |
| 7                                                       | .957  | .973  | .983  | .991  | .961  | .975  | .985  | .991  | .979  | .987  | .994  | .983  | .990  | .996  |  |
| 8                                                       | .960  | .976  | .986  | .993  | .963  | .977  | .987  | .993  | .981  | .988  | .995  | .984  | .991  | .997  |  |
| 9                                                       | .963  | .978  | .987  | .994  | .965  | .979  | .989  | .994  | .983  | .990  | .996  | .985  | .992  | .998  |  |
| 10                                                      | .965  | .980  | .989  | .995  | .967  | .981  | .990  | .995  | .984  | .991  | .997  | .986  | .993  | .998  |  |

| For 0% Effective Floor Cavity Reflectance (20% = 1.00) |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
|--------------------------------------------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Room Cavity Ratio                                      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 1                                                      | .859 | .870 | .879 | .886 | .873 | .884 | .893 | .901 | .916 | .923 | .929 | .948 | .954 | .960 |
| 2                                                      | .871 | .887 | .903 | .919 | .886 | .902 | .916 | .928 | .926 | .938 | .949 | .954 | .963 | .971 |
| 3                                                      | .882 | .904 | .915 | .942 | .898 | .918 | .934 | .947 | .936 | .950 | .964 | .958 | .969 | .979 |
| 4                                                      | .893 | .919 | .941 | .958 | .908 | .930 | .948 | .961 | .945 | .961 | .974 | .961 | .974 | .984 |
| 5                                                      | .903 | .931 | .953 | .969 | .914 | .939 | .958 | .970 | .951 | .967 | .980 | .964 | .977 | .988 |
| 6                                                      | .911 | .940 | .961 | .976 | .920 | .945 | .965 | .977 | .955 | .972 | .985 | .966 | .979 | .991 |
| 7                                                      | .917 | .947 | .967 | .981 | .924 | .950 | .970 | .982 | .959 | .975 | .988 | .968 | .981 | .993 |
| 8                                                      | .922 | .953 | .971 | .985 | .929 | .955 | .975 | .986 | .963 | .978 | .991 | .970 | .983 | .995 |
| 9                                                      | .928 | .958 | .975 | .988 | .933 | .959 | .980 | .989 | .966 | .980 | .993 | .971 | .985 | .996 |
| 10                                                     | .933 | .962 | .979 | .991 | .937 | .963 | .983 | .992 | .969 | .982 | .995 | .973 | .987 | .997 |

**Figure 9-29.** Multiplying Factors for Effective Floor Cavity Reflectances Other Than 20% (0.2)

If the maintained average wall exitance or the maintained average ceiling cavity exitance is required, a light loss factor is introduced into these equations in the same manner as for maintained average illuminance. For suspended luminaires the average ceiling cavity exitance obtained is the average exitance of the imaginary plane at the level of the luminaires. This exitance does not include the weighted average exitance of the luminaires as seen from below. It is rather the average exitance of the background against which the luminaires are seen. In the case of recessed or ceiling-mounted luminaires, the average ceiling cavity exitance obtained is the average exitance of the ceiling between luminaires.

**Limitations.** The limitations for exitance calculations are similar to those for average illuminance. In addition, the wall reflectance used to enter the tables is a weighted average of the reflectances for the various parts of the walls; the wall exitance found from the wall exitance coefficient is the value that would occur if the walls were of a uniform and perfectly diffuse reflectance equal to the average reflectance used. Thus, many parts of the wall may have exitance values that differ from the calculated average value. A correction can be applied to determine the approximate exitance of any part of the wall. For any area on the wall,

$$\text{exitance} = \frac{(\text{average wall exitance}) \times (\text{reflectance of area})}{\text{average wall reflectance}} \quad (9-61)$$

## The Lumen Method Applied to Partitioned Spaces

The lumen method can be applied to partitioned spaces by separating the room cavity into both an upper cavity that extends from the top of the partitions to the luminaire plane, and a second cavity that is the cavity within the partitioned area. The upper cavity has an area that is equal to the area of the room, and the lower cavity covers only the area included within a single partitioned zone. Two lumen method calculations need to be made in order to perform a complete analysis (see Example 1 in "Examples of Basic Lighting Calculations," in this chapter).

| Floor Cavity Reflectance ( $\rho_{cc} = 20\%$ ) |    |    |    |    |   |
|-------------------------------------------------|----|----|----|----|---|
| Wall Reflect-<br>tance $\rho_w$ (Per-<br>cent)  | 70 | 50 | 30 | 10 | 0 |

| RCR |      |      |      |      |      |
|-----|------|------|------|------|------|
| 0   | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 1   | .90  | .88  | .86  | .84  | .84  |
| 2   | .81  | .77  | .74  | .71  | .70  |
| 3   | .74  | .69  | .64  | .61  | .59  |
| 4   | .67  | .61  | .56  | .52  | .50  |
| 5   | .61  | .54  | .49  | .44  | .42  |
| 6   | .56  | .44  | .43  | .38  | .36  |
| 7   | .52  | .44  | .38  | .33  | .31  |
| 8   | .48  | .39  | .33  | .29  | .27  |
| 9   | .44  | .35  | .29  | .25  | .23  |
| 10  | .41  | .32  | .26  | .22  | .20  |

**Figure 9-30.** Coefficients of Utilization for a Perfectly Diffuse Emitter

First, the calculation is performed for the upper cavity to determine the illuminance falling on the top of the partitions. The floor cavity for this analysis is the area below the top of the partitions, and the effective floor cavity reflectance is that of a single partitioned space as viewed from above. All of the room's luminaires are used in this analysis, since presumably they all contribute to the illuminance on the plane at the top of the partitions. The CU is determined for the appropriate cavity ratio, and the average illuminance on the top of the partitions is then determined.

Next, the coefficient of utilization for the lower cavity, the area within a single partition, is considered. The coefficient of utilization is determined for a virtual luminaire that has a lambertian distribution, using [Figure 9-30](#). The appropriate wall and effective floor cavity reflectances are used to obtain this value. The effective ceiling cavity reflectance assumed in this table is zero, since interreflections between the upper and lower room cavities were already considered in the determination of the illuminance on the top of the partitions. In many partitioned spaces, each cubicle has only three sides formed by the partitions, with the fourth side being open. For the wall reflectance, an area-weighted average of the cubicle walls should be used, where the opening is assigned a reflectance of zero. The illuminance obtained at the top of the partitions is then multiplied by the coefficient of utilization obtained for the cubicle area to obtain the average illuminance on the workplane. The equation is summarized below:

$$E = \frac{\left( \begin{array}{c} \text{total bare} \\ \text{lamp lumens} \end{array} \right) \times CU_{\text{upper cavity}} \times CU_{\text{cubicle}} \times LLF}{\text{area of workplane}} \quad (9-62)$$

This procedure is likely to be more accurate for indirect lighting systems than for direct, since the procedure assumes that flux is entering the partition from above in a perfectly diffuse manner. Luminaires that direct light predominantly downward are likely to exhibit slightly higher illuminance values than this procedure determines.

# CALCULATION OF EQUIPMENT-RELATED QUANTITIES

So far in this chapter, quantities that characterize the lighting within a room have been discussed. Another set of quantities characterizes the luminaire. These include coefficients of utilization, optical efficiency, and the spacing criterion.

## Lumen Method Coefficients of Utilization<sup>31,45,82-84</sup>

CU tables, wall exitance coefficients, and ceiling cavity exitance coefficients can be prepared. It is desirable to have standard tables for these values to prevent misunderstandings and to facilitate direct comparisons of the data for different luminaires. These coefficients are derived from the equations described in the above section, "Basic Principles." There are five basic assumptions used to develop the zonal-cavity coefficients:

- Room surfaces are lambertian reflectors.
- The incident flux on each surface is uniformly distributed over that surface.
- The luminaires are uniformly distributed throughout the room (uniformly dense but not necessarily in a uniform pattern).
- The room is empty.
- The room surfaces are spectrally neutral.

Figure 9-28 shows the recommended form for unabridged CU tables. It is recognized that space limitations often necessitate abridgements. In that case, only the columns for  $\rho_{CC} = 80, 50,$  and  $10\%$  are recommended for luminaires having 0 to 35% of their output in the 90 to 180° zone; and 80, 70, and 50% for luminaires having over 35% of their output in that zone. Also, the  $\rho_{CC} = 10\%$  columns are not required for abridged tables. It is recommended that CUs be published to two decimal places, wall exitance coefficients to three decimal places, and ceiling cavity exitance coefficients to three decimal places. A wall direct radiation coefficient (WDRC) should be published to three decimal places for every room cavity ratio, adjacent to the wall exitance coefficient table. The three significant figures are not justified in terms of coefficient accuracy but are required because certain computational methods require the small differences between these coefficients.

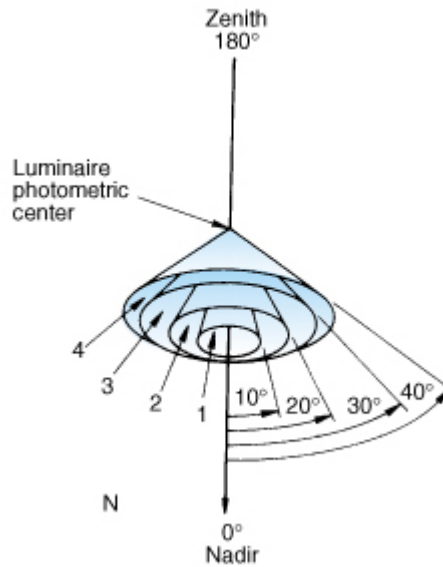
## Computation

1. Define 18 conic solid angle zones of 10° width from the nadir to the zenith about the luminaire as shown in [Figure 9-31](#), where the index of each zone,  $N$ , is an integer between 1 and 18 inclusive.
2. Determine the flux  $\Phi_N$  (lumens) in the various zones:
  - a. The flux in a conic solid angle ([Figure 9-32](#)) is given by

$$\Phi_N = 2 \pi I_{\theta_N} (\cos(\theta_N) - \cos(\theta_{N+1})) \quad (9-63)$$

where

$I_{\theta N}$  = midzone intensity, in cd, for the  $N$ th zone,  $\theta_N, \theta_{N+1}$  = bounding cone angles.



**Figure 9-31.** Conic solid angle zones of 10° width for use in calculating zonal flux.

b. If the intensity is not rotationally symmetric about the vertical axis, average the intensity about the vertical axis at each vertical angle  $\theta$ . Note that the intensity must be sampled at equal angular intervals about the vertical axis. For example, if the intensity is known for three vertical planes [ $I_{\theta, 90^\circ}$  (perpendicular),  $I_{\theta, 45^\circ}$  and  $I_{\theta, 0^\circ}$  (parallel)], then

$$I_{\theta} = \frac{1}{4} (I_{\theta, 0^\circ} + 2I_{\theta, 45^\circ} + I_{\theta, 90^\circ}) \quad (9-64)$$

Although three planes are sufficient for luminaires of nominal rotational symmetry, photometric data at 15° or 22.5° increments about the vertical axis are preferred for luminaires without this symmetry.

c. If the intensity is taken at 10° vertical intervals ( $\theta = 5^\circ, 15^\circ, 25^\circ, \dots$ ), then the flux  $\Phi_N$  is determined by the application of the equation in part (a), above, to the full zone. It is preferred to have intensity values at 5° vertical angles ( $\theta = 2.5^\circ, 7.5^\circ, 12.5^\circ, \dots$ ). Then zone  $N$  is divided into two parts, the equation is applied to each part, and the resulting flux is summed.

3. Determine the additional flux functions:

$$\Phi_{\text{luminaire}} = \sum_{N=1}^{18} \Phi_N \quad (9-65)$$

$$\eta_{\text{luminaire}} = \frac{1}{\Phi_{\text{total}}} \sum_{N=1}^9 \Phi_N \quad (9-66)$$

$$\eta_{\text{down}} = \frac{\Phi_{\text{lamps}}}{\Phi_{\text{lamps}}} \sum_{N=1}^{18} \Phi_N$$

$$\eta_{\text{up}} = \frac{1}{\Phi_{\text{lamps}}} \sum_{N=10}^{18} \Phi_N \quad (9-67)$$

where

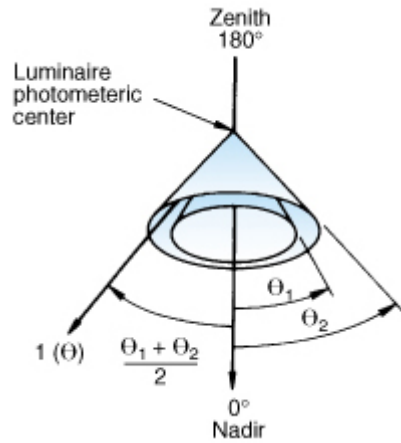
$\Phi_{\text{lamps}}$  = total flux emitted by the lamps,

$\Phi_{\text{luminaire}}$  = total flux emitted by the luminaire,

$\eta_{\text{down}}$  = proportion of lamp flux leaving the luminaire in a downward direction,

$\eta_{\text{up}}$  = proportion of lamp flux leaving the luminaire in an upward direction.

4. Determine the direct ratio,  $D_{\text{RCR}}$ , related to the fraction of luminaire flux below the horizontal that is directly incident on the workplane:



**Figure 9-32.** Angles used in calculating zonal flux.

$$D_{\text{RCR}} = \frac{1}{\eta_{\text{down}} \Phi_{\text{lamps}}} \sum_{N=1}^9 K_{\text{RCR},N} \Phi_N \quad (9-68)$$

where

RCR = room cavity ratio, used here as an integer between 1 and 10 inclusive,

$K_{\text{RCR},N}$  = zonal multipliers.

The zonal multiplier is the fraction of downward-directed flux directly incident on the workplane (lower surface of room cavity) for each zone  $N$ . The zonal multipliers are functions of the RCR:

$$K_{RCR,N} = e^{-A \cdot RCR^B} \quad (9-69)$$

where  $A$  and  $B$  are constants and are given in [Figure 9-33](#).

5. Determine the parameters  $C_1$ ,  $C_2$ ,  $C_3$ , and  $C_0$  as an intermediate step. In the formulas below,  $\rho_W$  is the wall reflectance,  $\rho_{CC}$  is the ceiling cavity reflectance, and  $\rho_{FC}$  is the floor cavity reflectance, which is taken as 0.2 for standard coefficient tables.  $F_{CC \rightarrow FC}$  is the form factor from the ceiling cavity to the floor cavity, described above in the discussion of flux transfer theory in the above section, "Basic Principles":

$$C_1 = \frac{(1 - \rho_W)(1 - f_{CC \rightarrow FC}^2)RCR}{2.5\rho_W(1 - f_{CC \rightarrow FC}^2) + RCR f_{CC \rightarrow FC}(1 - \rho_W)} \quad (9-70)$$

$$C_2 = \frac{(1 - \rho_{CC})(1 + f_{CC \rightarrow FC})}{1 + \rho_{CC} f_{CC \rightarrow FC}} \quad (9-71)$$

$$C_3 = \frac{(1 - \rho_{FC})(1 + F_{CC \rightarrow FC})}{1 + \rho_{FC} f_{CC \rightarrow FC}} \quad (9-72)$$

$$C_0 = C_1 + C_2 + C_3 \quad (9-73)$$

6. Determine the coefficient of utilization (CU), the wall exitance coefficient (WEC), and the ceiling cavity exitance coefficient (CCEC) for each applicable combination of reflectances and RCR:

| Zone (N) | A     | B    |
|----------|-------|------|
| 1        | 0     | 0    |
| 2        | 0.041 | 0.98 |
| 3        | 0.070 | 1.05 |
| 4        | 0.100 | 1.12 |
| 5        | 0.136 | 1.16 |
| 6        | 0.190 | 1.25 |
| 7        | 0.315 | 1.25 |
| 8        | 0.640 | 1.25 |
| 9        | 2.10  | 0.80 |

**Figure 9-33.** Constants for the Zonal Multiplier Equation

$$CU = \frac{2.5\rho_W C_1 C_3 (1 - D_{RCR})\eta_{down}}{RCR (1 - \rho_W)(1 - \rho_{FC}) C_0}$$

$$\rho_{CC} C_2 C_3 \eta_{up}$$

$$+ \frac{\rho_{CC} \rho_{FC} C_1 C_2 \eta_{up}}{(1 - \rho_{CC})(1 - \rho_{FC}) C_0}$$

$$\left( 1 - \frac{\rho_{FC} C_3 (C_1 + C_2)}{(1 - \rho_{FC}) C_0} \right) \frac{D_{RCR} \eta_{down}}{1 - \rho_{FC}} \quad (9-74)$$

$$\begin{aligned} WEC = & \frac{2.5 \rho_W (1 - D_{RCR}) \eta_{down}}{RCR (1 - \rho_W)} \\ & \times \left( 1 - \frac{2.5 \rho_W C_1 (C_2 + C_3)}{RCR (1 - \rho_W) C_0} \right) \\ & + \frac{2.5 \rho_W \rho_{CC} C_1 C_2 \eta_{up}}{RCR (1 - \rho_W) (1 - \rho_{CC}) C_0} \\ & + \frac{2.5 \rho_W \rho_{FC} C_1 C_3 D_{RCR} \eta_{down}}{RCR (1 - \rho_W) (1 - \rho_{FC}) C_0} \quad (9-75) \end{aligned}$$

$$\begin{aligned} CCEC = & \frac{2.5 \rho_W \rho_{CC} C_1 C_2 (1 - D_{RCR}) \eta_{down}}{RCR (1 - \rho_W) (1 - \rho_{CC}) C_0} \\ & + \frac{\rho_{CC} \eta_{up}}{1 - \rho_{CC}} \left( 1 - \frac{\rho_{CC} C_2 (C_1 + C_3)}{(1 - \rho_{CC}) C_0} \right) \\ & + \frac{\rho_{CC} \rho_{FC} C_2 C_3 D_{RCR} \eta_{down}}{(1 - \rho_{CC}) (1 - \rho_{FC}) C_0} \quad (9-76) \end{aligned}$$

7. Determine the wall direct radiation coefficient (WDRC) for each RCR:

$$WRDC = \frac{2.5 \eta_{down} (1 - D_{RCR})}{RCR} \quad (9-77)$$

8. The above equations can be used to calculate the CU, WEC, and CCEC when the RCR equals zero, but the forms of the equations must be arranged to avoid division by zero. It is simplest to use the following relationships:



$$CU_{RCR=0} = \frac{\eta_{down} + \rho_{CC}\eta_{up}}{1 - \rho_{CC}\rho_{FC}} \quad (9-78)$$

$$CCEC_{RCR=0} = \frac{\rho_{CC}(\eta_{up} + \rho_{FC}\eta_{down})}{1 - \rho_{CC}\rho_{FC}} \quad (9-79)$$

## Luminaire Efficiency

The luminaire efficiency is simply the ratio of the lumens leaving the luminaire to the total lumens produced by the lamps. From the expressions above, this quantity is

$$\text{luminaire efficiency} = \frac{\Phi_{\text{luminaire}}}{\Phi_{\text{lamps}}} \quad (9-80)$$

The luminaire efficiency is considered in the determination of the CU.

## Average Luminaire Luminance

The average luminaire luminance is a means of evaluating the effect that a luminaire has on visual comfort, as well as veiling reflections on task surfaces such as VDTs. A value can be easily determined in any direction, given the photometric characteristics of the luminaire. Since luminance is expressed in candelas per unit area, the average luminance in a direction  $(\theta, \psi)$  (specified in spherical coordinates) is

$$L(\theta, \psi)_{\text{avg}} = \frac{I(\theta, \psi)}{A_{\text{luminaire}} \cos \theta} \quad (9-81)$$

where

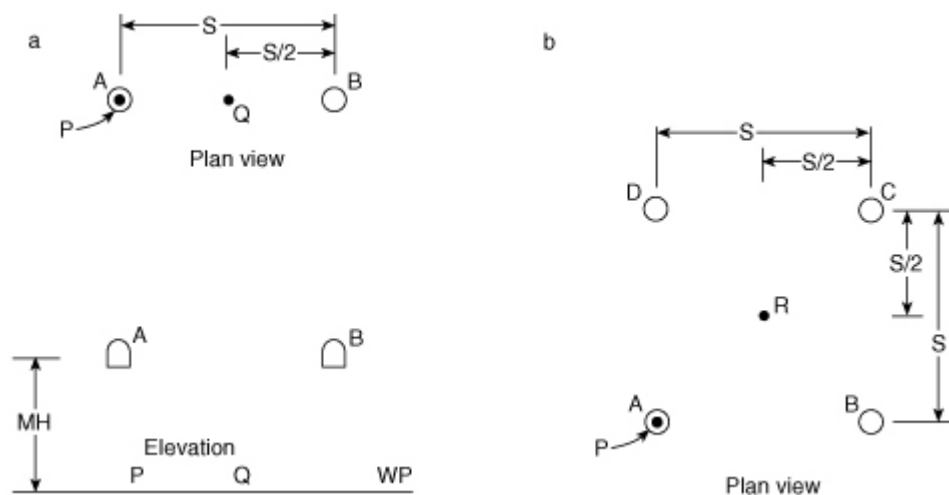
$I(\theta, \psi)$  = intensity of the luminaire in the direction  $(\theta, \psi)$ ,  
 $A_{\text{luminaire}}$  = surface area of the luminous element(s) of the luminaire.

## Luminaire Spacing Criterion

The luminaire spacing criterion<sup>85</sup> (SC) is a classification technique for interior luminaires relating to the spread or distribution of the direct illuminance on a horizontal plane. It tests the uniformity of horizontal illuminance at two pairs of selected points to estimate the probable extreme limit of acceptable luminaire spacing. It is not a specification of the spacing-to-mounting-height ratio to be used in a lighting installation, and in fact, installation of luminaires at this nominal value may produce a poor lighting system.

The purpose of this classification technique is to aid designers in rapidly assessing one aspect of the potential of a luminaire with respect to its applications. It gives some idea about the distribution of flux from a luminaire and its subsequent effect on lighting system parameters, using only a single number. The basis of the luminaire spacing criterion is the horizontal illuminance on the workplane due to direct illuminance from nearby luminaires. As a first approximation it is assumed that this represents a limiting case, since the reflected component of

approximation, it is assumed that this represents a limiting case, since the reflected component of illuminance and the illuminance due to more distant luminaires generally increases the uniformity of horizontal illuminance from point to point.



**Figure 9-34.** Points  $Q$  and  $R$  represent points of most probable low illuminance for (a) a configuration of 2 luminaires, and (b) a square array of 4 luminaires.

When two similar conventional luminaires are near their maximum spacing, the illuminance directly under a luminaire ( $P$ ) is principally due to the overhead luminaire ( $A$ ) (Figure 9-34a). Further, a very probable point of low illuminance is at the midpoint between two luminaires ( $Q$ ). The maximum spacing at a given mounting height above the workplane is chosen such that the illuminance halfway between the two luminaires ( $Q$ ) due to both luminaires ( $A$  and  $B$ ) equals the illuminance under one ( $P$ ) due to that one luminaire ( $A$ ) only. Another likely point ( $R$ ) for low illuminance is at the center of a square array of adjacent luminaires (Figure 9-34b). The maximum spacing at a given mounting height above the workplane is chosen such that the illuminance at the center of the luminaires ( $R$ ) due to all four luminaires ( $A$ ,  $B$ ,  $C$ , and  $D$ ) equals the illuminance under one ( $P$ ) due to that one luminaire ( $A$ ) only. The maximum spacing (expressed as a spacing-to-mounting-height ratio that is unitless) that fulfills each of the above conditions is easily determined on a special graph (Figure 9-35) using the intensity distribution of the luminaire. For the purpose of establishing this criterion, it is assumed that the inverse square law is valid. This is the only assumption for the computations.

**Procedure.** The procedure for calculating the luminaire spacing criterion is as follows:

A. For luminaires whose intensity distribution is nominally symmetric about the nadir:

1. Plot the relative intensity of the luminaire on the chart of Figure 9-35.
2. Locate the point of one-half the intensity at  $0^\circ$  on the ordinate, and draw a line through that point and parallel to the diagonal lines. If the intensity varies significantly in the vicinity of  $0^\circ$ , use an average of the intensity over the  $0$  to  $5^\circ$  polar angle.
3. Read scale  $A$  above the intersection of this line with the intensity curve.
4. Repeat step 2 using the point of one-quarter the intensity at  $0^\circ$ .

5. Read scale *B* above the intersection of this line with the intensity curve.

6. The lower of the values found in steps 3 and 5 is the luminaire spacing criterion. Round off the value to the nearest 0.1.

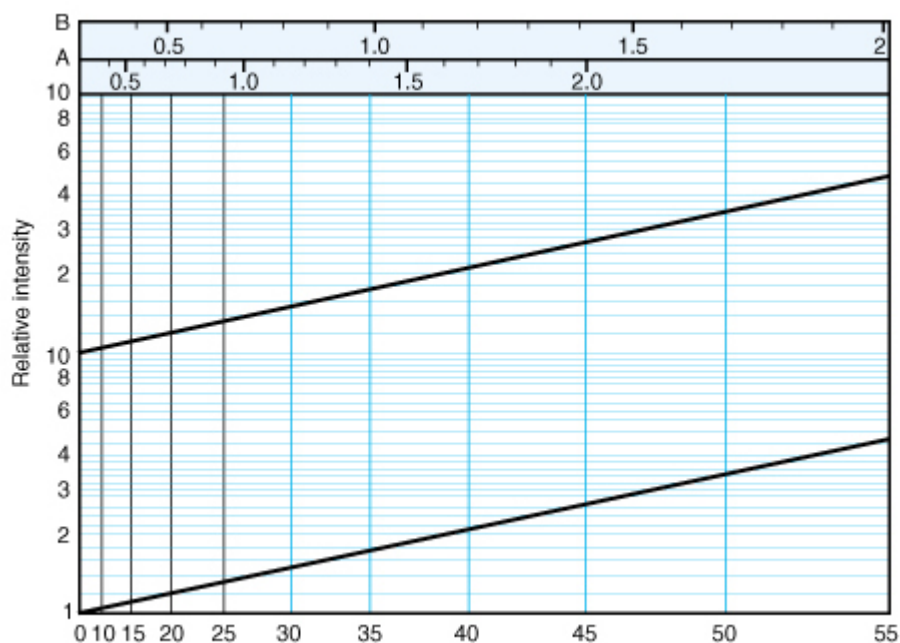
B. For luminaires with significantly asymmetric intensity distributions about the nadir:

1. Independently evaluate the intensity distributions in the parallel and perpendicular ( $0^\circ$  and  $90^\circ$ ) planes.

2. Apply steps 1, 2, and 3 from part A above for each of the intensity curves. Round off to the nearest 0.1.

3. In some cases, it may be appropriate to evaluate the intensity distribution in the  $45^\circ$  plane.

**Interpretation.** The value from scale *A* corresponds to the luminaire spacing criterion at point *Q* (Figure 9-34a), and the value from scale *B* corresponds to this criterion at point *R* (Figure 9-34b). Thus for symmetrical intensity distributions, the luminaire spacing criterion requires the direct horizontal illuminance at both test points to be equal to or greater than the illuminance directly below a single luminaire. For nonsymmetrical intensity distributions, it is generally found that independent testing at point *Q* for each orientation is adequate. A point directly under a luminaire has relatively high illuminance and receives its principal contribution from the luminaire overhead when the spacing is large. If the illuminance at a probable low point due to the closest luminaires is no lower than that at a probable high point, due to the main component, then it is likely that reasonable uniformity is achieved over the entire workplane. The luminaire spacing criterion only suggests a maximum spacing at which the horizontal illuminance is reasonably uniform. When other criteria are considered, such as overlap between luminaires, vertical illuminance, shadowing, and illuminance distribution above the workplane, it generally is found that luminaires must be installed at some spacing-to-mounting-height ratio less than the value of the luminaire spacing criterion.



**Figure 9-35.** Chart for determining the luminaire spacing criterion.

In cases where uniformity is particularly important, the lighting designer must calculate the illuminance at several points throughout the room. It is suggested that a maximum value of 1.5 be assigned as the luminaire spacing criterion for any luminaire, since the use of larger values frequently does not produce acceptable lighting installations when all performance criteria are examined. Also, certain luminaires are designed to be installed only with specific spacing relations, and neither larger nor smaller spacings are desirable. In such cases, a luminaire spacing criterion is not applicable. Specific limits or ranges for the spacing-to-mounting-height ratios should be recommended by the manufacturer, and the basis for the recommendation should be stated, such as a certain degree of horizontal illuminance uniformity (determined by point calculations). In addition to the luminaire spacing criterion, it is possible to determine illuminance uniformity for specific installation conditions and report spacing-to-mounting-height limits for such conditions. If that is done, the luminaire layout, the room conditions, the uniformity criteria, and any application restrictions should be explicitly described.

## INTERPRETATION AND LIMITS OF CALCULATED QUANTITIES

Calculated quantities can be used to provide the designer of a lighting system with information that could not otherwise be obtained except with an actual mock-up of a lighting installation. Information on illuminance, luminance, exitance, contrast, visual comfort probability, visibility, and visual performance metrics can be used to compare alternative designs and to verify that design criteria are met. These calculated quantities can also be used to protect or challenge a specification. Calculations are often required to meet strict design requirements imposed by labor unions, owners, local codes, or the like. If used correctly, computer models can be a valuable asset in designing a lighting system to meet particular design criteria.

With recent advances in the field of computer graphics, it is now possible to view the effects of a lighting system on a room through a computer-generated rendering of a space. At the heart of these renderings is a complex lighting analysis. The transformation from luminance data to a realistic-looking synthetic image requires special attention, since a computer screen has a limited range of available luminances. These tools are now being used by lighting professionals to evaluate and market their designs. Further improvements in this process will certainly make computer-generated visual methods more popular in the future.

In reviewing any lighting calculations, the results should first be screened for possible errors. Improper orientation or placement of a luminaire may produce incorrect results. Improper photometry, lamp lumen output, or light loss factors may also cause errors. If the results appear unreasonable, an error may be producing an inaccurate result. Assuming that the results are for the proper arrangement of lighting equipment and room surfaces, some advice is provided below to help evaluate computer output.

### Illuminance

Often a designer has selected a target illuminance, and a detailed analysis is performed to determine if the target value is provided. For maintained illuminance, a design is generally acceptable if the illuminance is within 10% of the target value. For energy conservation purposes, values below the target value are preferred over values above.

It is difficult, however, to achieve a uniform value everywhere within a space, or even across a

It is difficult, however, to achieve a uniform value everywhere within a space, or even across a desk or workplane. A 15% variation in illuminance is generally considered to be tolerable. In all cases it is the responsibility of the designer to determine if a particular variation is acceptable.

In evaluating illuminance, it is important to focus on the actual task locations. Most general lighting systems provide a higher illuminance in the middle of the room than near the walls. If the principal task locations are against the walls, a more detailed analysis may be needed to properly evaluate the illuminance at those areas.

Obstructions in a space, such as partitions, should be considered in a lighting calculation model if possible. If an empty room is modeled, the illuminance near a vertical partition is likely to be much lower than predicted.

## Luminance

Luminances can be used to evaluate the appearance of a space. Scallops, sharp luminaire cutoffs, and the general pattern of brightnesses can be studied through numerical and graphical models. Computer renderings or simple luminance contours for room surfaces can provide the needed information for a designer to evaluate the performance of lighting equipment.

Luminances can also be evaluated with respect to a luminance ratio criterion. In the lighting of spaces containing VDTs, the uniformity of the luminance on the ceiling and the maximum ceiling luminance are critical aspects to study (see [Chapter 11](#), Office Lighting).

## Contrast

The calculation of task contrast, particularly for specular tasks, provides an indication of where veiling reflections occur within a space. Contrast can also be used to compare the performance of two different lighting systems. Visibility and visual performance metrics that use task contrast can provide some insight into the significance of the contrast and the task luminance provided by a lighting system.

## Visual Comfort Probability

Visual comfort probability (VCP) is a metric with limited application. It was developed for lensed fluorescent lighting equipment. It is not valid for use with incandescent or HID equipment. It also cannot be used with luminaires that have an upward component. The procedure has never been proven to accurately model the discomfort caused by parabolic fluorescent luminaires, although many lighting professionals continue to apply it in such situations. Parabolic luminaires are much less uniform in luminance than lensed luminaires, and the difference can have a noticeable effect on the comfort of occupants.

Small differences in VCP are not significant. VCP differences of less than 5 points do not indicate a meaningful difference in discomfort glare potential.

## Comparison of Calculated and Measured Quantities

Although it seems reasonable to expect calculated values of quantities to be reproduced in the field, in practice it is very difficult to reconcile measured quantities with those provided by calculation. Assumptions inherent in any calculation model often represent conditions very different from those in an actual lighting installation.<sup>1</sup> Some of these conditions are listed below:

- Lambertian surfaces are assumed in most computer programs. Real-world surfaces may

contain some degree of specularity.

- The room surface reflectance input to analysis software may not accurately represent what is present in the field.
- Reduced electrical voltage in the power system may produce reduced light output.
- The assumed ballast factor may be much different from that present in the field.
- Thermal effects in an installed luminaire may alter light output.
- Minor differences incurred in the manufacturing process or in the positioning of the lamp within a luminaire may alter the luminaire's photometric distribution.

Furniture and other absorbing and reflecting surfaces may not have been considered in the computer model. No analysis model is an exact representation of any real room. Simplifying assumptions in the calculation method may limit the accuracy of the results. Far-field photometric methods applied in a near-field situation may not accurately model the luminaire performance.

Another reason for disagreement can be errors in the measurement process. It is important to follow strict guidelines when measuring the photometric performance of lighting systems. For example, it is important that the lighting system be measured at a temperature that is representative of its thermal equilibrium condition. New lamps should operate for at least 100 h before measurements are taken. The operator of a photometer must ensure that his or her own presence does not influence the reading. Orientation and positioning of the photometer are also critical; a tripod with a leveling device is particularly useful when conducting horizontal illuminance measurements. Finally, all daylight should be eliminated from the measurements on interior lighting systems, perhaps by conducting measurements at night. Any attempt to subtract out daylight levels is difficult and is likely to introduce errors because of the temporal variations in daylight illuminance.

The magnitude of the differences between detailed analysis methods and field measurements varies. In general, differences of less than 20% can be expected, but in extreme cases, where a calculation method simply cannot handle the complexity of the lighting system, they may be greater. For a more complete discussion of the uncertainties, see reference 83.

## EXAMPLES OF BASIC LIGHTING CALCULATIONS

The purpose of this section is to show how to apply some of the equations and procedures described in previous sections to lighting problems. Seven practical lighting problems demonstrate the calculation of basic quantities. With the exception of visual task contrast, the calculation of derived quantities is not demonstrated, nor are equipment-related quantities calculated, because these are normally calculated by manufacturers of lighting equipment.

The following outline helps organize the basic lighting calculation procedures and in fact represents the order in which basic calculations are often performed.

First-order calculations: illuminance

### 1. Direct calculations

A. Diffuse, lambertian emission

B. Real (nondiffuse) emission distributions

## 2. Interreflection calculations

### Second-order calculations: luminance

1. Diffuse, lambertian reflection
2. Real, (bidirectional) reflectance distributions

The first-order calculations are used to characterize the light reaching a surface, that is, the illuminance. The illuminance on a surface is a result of the light reaching that surface directly and by interreflections from surrounding surfaces. Luminance describes how light makes objects and surfaces appear and includes determination of contrast and luminance ratios. The determination of luminance is a second-order calculation because it almost always follows an illuminance calculation.

The first-order (illuminance) calculations are of two types. The first type is used to determine how much light reaches a surface or a point directly from a luminous source. The second type is used to determine how much light reaches the same surface or point from a secondary source of light that is, in fact, luminous by reflection.

Direct illuminance, either averaged over a surface or at a point on a surface, is treated as if produced by light emitted directly from a point source (as in the case of an incandescent lamp downlight), a line source (a narrow fluorescent lamp luminaire), or an area source (a window). These direct illuminance calculations assume one of two types of emitters, diffuse or nondiffuse.

Diffuse emitters are idealized approximations of reality that make calculations simpler to perform. Such emitters follow Lambert's cosine law of emission. This approximation is useful and appropriate for some reflective materials, such as cloth-covered partitions and flat-latex-painted walls, and for some transmissive materials, such as the face of a white plastic sign. Some self-luminous sources, such as the surface of a fluorescent lamp, can also be considered diffuse emitters.

Nondiffuse emitters have specific luminous intensity distributions determined by photometric measurement. In this section, they are referred to as real emitters. Luminaires are almost always treated as real emitters.

Interreflection is the repeated reflection of light among surfaces. For interreflection calculations, surfaces are always assumed to be diffuse reflectors. These surfaces are of finite area, their number and sizes dictated by the accuracy needed for the calculation. More surfaces of smaller size are specified for more accurate interreflection calculations. Interreflection calculations lead to surface exitance values, which are then used as sources of illumination. These values produce a quantity called the interreflected component in the illuminance calculation.

For some illuminance calculations, such as those for an indirect electric lighting system, only the interreflections are relevant. For some direct lighting systems, interreflections are negligible contributors to the total illuminance; in these cases, an experienced designer does not bother to calculate them (see the section "Characterizing Light for Calculation Purposes").

The second-order (luminance) calculations in this section are for luminance produced by reflection. That is, once light reaches a surface, the reflection characteristics of the surface determine its luminance. There are two types of luminance calculations: those for surfaces that can be approximated by diffuse reflection (that is, those that follow Lambert's cosine law of



reflection), and those requiring specificity as to the bidirectional reflectance characteristics of the surface. Bidirectionality means that the reflectance of the surface depends on both the incident and the exitant directions of light. All real surfaces are characterized by a bidirectional reflectance distribution function (BRDF). Luminance calculations for real surfaces are the only ones for which the direction of incident light is important. Luminance by transmission is not considered in this section.

## A General Algorithm for Lighting Calculations

The following discussion presents a general algorithm for lighting calculations. It consists of six steps:

1. Determine the quantity to be calculated.
2. Identify luminaires and the information describing them.
3. Determine the accuracy, complexity, and detail of the calculation.
4. Identify required geometric, reflectance, and other ancillary data.
5. Determine the appropriate equations or computational procedure.
6. Solve the equations or complete the procedure.

**1. Determine the Quantity to Be Calculated.** An evaluation of the proposed lighting system is the first step in the lighting calculation process. This evaluation includes a determination of what needs to be calculated and the required accuracy of the calculation. Listed in order of increasing complexity are the quantities considered in this section of example calculations:

- Average illuminance on a surface
- Illuminance at a point
- Average exitance and average diffuse luminance of a surface
- Exitance and diffuse luminance at a point
- Nondiffuse luminance

These basic quantities are used in a wide range of lighting applications. Computational procedures to determine them are independent of the specific lighting application in which they are used. Some applications, such as sports and roadway lighting, use coordinate systems and light loss factors in ways characteristic to those applications (see [Chapter 20](#), Sports and Recreational Area Lighting, and [Chapter 22](#), Roadway Lighting).

The value in performing these calculations is that they help demonstrate what is and is not important for a lighting design. For example, surface reflectances can significantly affect the lighting power density required to bring the illuminance levels to those required in an indoor space.

**2. Identify Luminaire Geometry and Luminous Intensity Distribution.** For computational purposes, sources can be categorized by the size and the dimensions they exhibit relative to the distances involved in the computation. It is usual to use the five-times rule to make this determination. This rule states that if the distance between the luminaire and the computation



point is more than five times a luminaire's largest dimension, the luminaire can be treated as a point source. Thus, it is the ratio of luminaire size to computation distance that governs the computational size or geometry category of the luminaire (see the section "Photometry as the Basis for Calculations"). Assuming a luminaire to be a luminous rectangle, the following criteria hold:

- If both of its dimensions are smaller than one-fifth the computation distance, the luminaire is considered a point source.
- If only one dimension is larger than one-fifth the computation distance, the luminaire is considered a line source.
- If both dimensions are larger than one-fifth the computation distance, the luminaire is considered an area source.

Some examples of point, line, and area sources are:

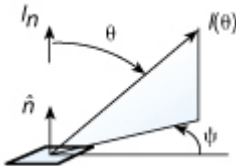
| Geometry | Examples                                                                                                                                                                                                                                                                                                                                                                                         |
|----------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Point    | 75-W incandescent A lamp in an 8-in.-diameter downlight, used in an office with 8-ft ceilings<br>1000-W metal halide industrial luminaire with a 24-in. reflector mounted 25 ft above the floor                                                                                                                                                                                                  |
| Line     | 4-ft unshielded T-12 fluorescent lamp in a small machine shop<br>6-in. × 4-ft wall-washer luminaire with two T-8 fluorescent lamps                                                                                                                                                                                                                                                               |
| Area     | 2 × 4-ft troffer with three T-12 fluorescent lamps and a prismatic lens in a classroom with 9-ft ceilings<br>2 × 2-ft parabolic troffer with two 39-W compact fluorescent lamps, recessed in a 10-ft ceiling and 4 ft from a wall on which luminances are to be calculated<br>4-in. × 2-ft luminaire with a 20-W T-5 fluorescent lamp and a prismatic lens mounted under a bookshelf over a desk |

For computational purposes, luminous intensity distributions are considered either diffuse or nondiffuse. For computational purposes a diffuse luminous intensity distribution ([Figure 9-36](#)) is defined as

$$I(\theta, \psi) = I_n \cos \theta$$

where

$I_n$  = luminous intensity normal ( $\hat{n}$ ) to the luminous surface,  
 $\theta$ , = declination angle measured from the normal,  
 $\psi$  = azimuthal angle.



**Figure 9-36.** Illustration of angles for a diffuse intensity distribution.

A diffuse luminous intensity distribution does not depend on the azimuthal angle  $\psi$  and is axially symmetric about the normal to the luminous surface. It exhibits an intensity that varies only with the cosine of the declination angle  $\theta$ .

If a luminaire has a luminous intensity distribution given by  $I(\theta, \psi)$ , and if the ratio

$$\frac{I(\theta, \psi)}{I(0^\circ, 0^\circ) \cos(\theta)}$$

differs from 1.0 by more than 10% for any of the intensities, then the distribution is considered to be nondiffuse. Large errors may result if such a distribution is treated as diffuse. Most luminous intensity distributions exhibited by electric lighting equipment are nondiffuse.

### 3. Determine the Accuracy and the Complexity

*Accuracy.* Accuracy requirements are different for different stages in the lighting design process. A preliminary determination of the type of source and required luminaire efficiency can be made, knowing the average illuminance that is required. An accuracy of  $\pm 100\%$  is generally sufficient for this determination. Then a preliminary choice of the general type and number of luminaires can be made, knowing the average illuminance that is required. An accuracy of  $\pm 25\%$  is generally sufficient for this stage. Illuminance calculations at a point require that both the specific luminous intensity distribution and location of the luminaire(s) be known. [Figure 9-37](#) provides guidance about the required accuracy at different stages of the design process.

| Available Information                    | Assumptions Needed to Perform the Calculations | Types of Calculations Possible                     | Approximate Accuracy |
|------------------------------------------|------------------------------------------------|----------------------------------------------------|----------------------|
| Lamp wattage and efficacy                | Luminaire efficiency                           | Average illuminance                                | $\pm 100\%$          |
| Lumen output of luminaire                | Luminous flux between $0^\circ$ and $45^\circ$ | Average illuminance                                | $\pm 25\%$           |
| Lamp lumens, coefficients of utilization | None                                           | Average illuminance, exitance, or diffuse exitance | $\pm 10\%$           |
| Luminous intensity distribution          | None                                           | Illuminance, exitance, or luminance at a point     | $\pm 5\%$            |

**Figure 9-37.** Expected Accuracy of Lighting Calculations

The importance of the result and the consequences of uncertainty determine the accuracy required of a calculation. The accuracy, in turn, determines the complexity and cost of the calculation. For purposes of assessing illuminance as it relates to vision- and visibility-related lighting system characteristics, an accuracy of  $\pm 25\%$  is probably sufficient. Luminances used for determining the

contrast of reading materials should be calculated with an accuracy of  $\pm 10\%$ . For specification, legal, or comparison purposes, calculations of  $\pm 5\%$  accuracy are often desired. A reasonable upper limit to what can be expected from computational accuracy is established by the uncertainty in measurement. Even with high-quality light measurement equipment,  $\pm 5\%$  accuracy is usually the best that can be expected. Computational accuracy greater than this cannot be verified by measurement.

*Complexity.* Calculation complexity is determined by the geometry of the problem. For example, an L-shaped room is computationally more complex than a rectangular room. Similarly, partition shadows and reflections add considerable complexity to the calculations; however, the complex calculations are more accurate.

The need for accuracy is often different for the direct and interreflected components. Although it may be necessary to calculate both the direct and interreflected components, the dominant component should always be calculated with much more accuracy. This, in turn, affects the complexity of the calculation.

#### 4. Identify Required Geometric, Reflectance, and Ancillary Data

*Geometric Data.* Room dimensions, partition sizes and locations, and surface orientation information such as the slope of a ceiling are necessary geometric information for calculations. Similarly, the luminaire sizes and locations must be determined.

*Reflectance Data.* Surface reflectances are often unknown at lighting design and calculation time. Unknown reflectances produce an uncertainty that can be determined by calculation. In such cases, those quantities affected by reflectance are calculated twice, using the lowest and highest reasonable values of reflectance that are likely to be present. If these two values lie outside the accuracy requirements listed in [Figure 9-37](#) and below in step 5, then a specification for surface reflectance is required. If the range is small, on the other hand, the reflectances can remain unknown, their values having been found not to significantly affect the lighting system's performance.

*Ancillary Data.* These data are often specific to a particular application. Examples of such data are BRDFs for visual tasks,  $r$  tables for roadway luminance calculations, application adjustment factors (AAFs) for sports lighting, and climate and site data for daylighting calculations. See the application chapters of this handbook for complete information on the ancillary data that might be required for a particular situation.

**5. Determine Appropriate Equations.** The appropriate equations for average workplane illuminance calculations are determined by the required accuracy. Note that the following equations should also include light loss factors in order to be accurate.

For direct lighting systems with an accuracy of  $\pm 100\%$ ,

$$E_{\text{ave}} = \frac{\text{lamp watts} \times \text{efficacy} \times \text{luminaire efficiency} \times \text{number of lamps}}{\text{lighted area}}$$

For indirect lighting systems with an accuracy of  $\pm 100\%$ ,

$$E_{\text{ave}} =$$

$$\frac{\text{lamp watts} \times \text{efficacy} \times \text{luminaire efficiency} \times \text{number of lamps} \times 0.80 \times \text{ceiling reflectance}}{\text{lighted area}}$$

The factor 0.80 above is a reasonable average value in most rooms for what is termed the form factor between the ceiling and floor. That is, for typical rooms, the fraction of luminous flux emitted by the ceiling that reaches the floor is 0.80.

For direct lighting systems and an accuracy of  $\pm 25\%$ ,

$$E_{\text{ave}} = \frac{\text{lamp lumens} \times \text{luminaire efficiency} \times \text{number of lamps} \times \text{fraction of luminaire lumens between } 0^\circ \text{ and } 45^\circ}{\text{lighted area}}$$

The amount between  $0^\circ$  and  $45^\circ$  is a reasonable value for the luminaire lumens that reach the floor directly in rooms of typical proportions. There is no equation for indirect lighting systems and an accuracy of  $\pm 25\%$ .

For both direct and indirect lighting systems and an accuracy of  $\pm 10\%$ ,

$$E_{\text{ave}} = \frac{\text{lamp lumens} \times \text{coefficient of utilization} \times \text{number of lamps}}{\text{lighted area}}$$

For an accuracy of  $\pm 5\%$ , the luminous intensity distribution must be known. The appropriate equations for direct component calculations follow from the geometry of the source, as shown in [Figure 9-38](#).

The appropriate equations for interreflected component calculations are obtained from radiative transfer. The room surfaces are divided into discrete elements and an exitance is calculated for each. More and smaller elements are required for more accurate interreflection calculations.

| Source Geometry | Equation                                    |                                                                                                        |
|-----------------|---------------------------------------------|--------------------------------------------------------------------------------------------------------|
|                 | Diffuse distribution                        | Nondiffuse distribution                                                                                |
| Point           | Inverse square cosine law                   | Inverse square cosine law                                                                              |
| Line            | Configuration factor for a line to a point  | Inverse square cosine law, where the line is discretized into pieces that are treated as point sources |
| Area            | Configuration factor for an area to a point | Inverse square cosine law, where the area is discretized into pieces that are treated as point sources |

**Figure 9-38.** Equations for Direct Component Calculations

**6. Solve the Equations** Hand calculation is appropriate for small problems with

**6. Solve the Equations.** Hand calculation is appropriate for small problems with straightforward equations. Spreadsheet programs can often be used. They are the useful option to specialized software, are easy to learn and use, and can be very powerful. More sophisticated computer programs are essential for complex, repetitive, or extended calculations.

# COORDINATE SYSTEMS FOR LUMINAIRE PHOTOMETRY

Many lighting calculations involve using luminous intensity distribution data provided by manufacturers in photometric reports. The two basic coordinate systems for luminaire photometry are the spherical coordinate system and the polar coordinate system.

Directions relative to a lamp or luminaire are specified in a spherical coordinate system by angles  $\theta$  (altitude) and  $\theta$  (azimuth). The convention often is used that an azimuth direction along the lamp axis is  $\psi = 0^\circ$  or  $\psi = 180^\circ$ , but when referring to data in a photometric report it is necessary to give careful attention to how the origin of  $\psi$  is defined. The terms and symbols used to describe a direction along the lamp axis are

along, parallel, ||,

and across the lamp axis

across, perpendicular, +.

A polar plot gives curves that specify the variation with  $\theta$  of  $I(\theta, \psi)$  in an azimuthal plane for stated angles  $\theta$ . The polar plot is scaled in candelas (cd) measured radially from the photometric center. If the luminous intensity distribution is constant about the vertical axis (as with a round downlight having a vertical lamp orientation), only one curve is given and the angle  $\psi$  is not specified. If the luminous intensity distribution is symmetric about both the parallel and perpendicular horizontal axes (as with a horizontally mounted fluorescent lamp), curves may be given only for angles from 0 to  $90^\circ$ . Such a distribution is called quadrilaterally symmetric. In this case, equivalent values of  $\psi$  for angles that are between  $90^\circ$  and  $360^\circ$  are calculated as follows:

| Range of $\psi$            | Equivalent Angle   |
|----------------------------|--------------------|
| $90^\circ$ to $180^\circ$  | $180^\circ - \psi$ |
| $180^\circ$ to $270^\circ$ | $\psi - 180^\circ$ |
| $270^\circ$ to $360^\circ$ | $360^\circ - \psi$ |

This equivalent angle is the lookup angle used in the table of luminous intensity values.

With less symmetry and increasing optical control complexity, polar plots require more azimuthal planes (and therefore more curves) to adequately define the performance of the luminaire. Sometimes the luminous intensity of a luminaire is required at an angle that is not listed in the photometric report. In such cases interpolation is necessary to obtain accurate results. Linear interpolation is the simplest form of interpolation and is used here, though other more complicated procedures are available.<sup>3,4</sup>

Figure 9-39 contains a partial luminous intensity table for an imaginary luminaire. Altitude angles are given at  $10^\circ$  intervals, and three azimuth angles are given ( $0^\circ$ ,  $45^\circ$ , and  $90^\circ$ ). To determine the luminous intensity for an azimuth angle of  $45^\circ$  and an altitude angle of, for example,  $42.7^\circ$ , the following procedure can be used.

The fraction equal to the difference between 40° and 42.7° over the difference between 40° and 50° should be calculated:

$$\frac{42.7^{\circ} - 40^{\circ}}{50^{\circ} - 40^{\circ}} = \frac{2.7^{\circ}}{10^{\circ}}$$

From the table, the intensity at 40° is 3012 cd and the intensity at 50° is 3133 cd. The difference between these two values is 3133 – 3012 = 121 cd, and 27% of this difference is 32.7 cd. This value is then added to the intensity at 40°. Thus the intensity at an altitude of 42.7° and an azimuth of 45° is estimated to be 3012 + 32.7 = 3044.7, or 3045 cd. A way to check that the interpolated value is correct is that it must lie between the bounding points in the table (3045 cd lies between 3012 and 3133 cd).

The examples that follow are taken from actual applications. They are intended to illustrate the general algorithm for lighting calculations discussed above. Only rarely would these examples represent a complete lighting calculation analysis. It is hoped, however, that the preceding discussion and the following examples lead to or augment an understanding of the invisible process of computer calculations. All of the following examples use English units of measurement (such as feet, inches, and footcandles). This is done to help facilitate an understanding of the basic calculations for the audience familiar with this system of units.

| Attitude<br>θ | Intensity (cd) at Azimuth, ψ |      |      |
|---------------|------------------------------|------|------|
|               | 0°                           | 45°  | 90°  |
| 0°            | 1866                         | 1866 | 1866 |
| 10°           | 2019                         | 2653 | 2304 |
| 20°           | 2431                         | 2721 | 2512 |
| 30°           | 2512                         | 2964 | 2581 |
| 40°           | 2639                         | 3012 | 2744 |
| 50°           | 2818                         | 3133 | 3008 |

**Figure 9-39.** Partial Example of a Luminous Intensity Distribution

Figure 9-40 summarizes the example calculations and their applications. The most useful and most widely applied calculations are those for illuminance, both at a point and averaged over a surface. All illustrations for these examples have been made using a computer drafting system similar to what might be used in many architectural and lighting design firms.

| Quantity Calculated    | Possible Applications                                                                                                                             | Example*                          |
|------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------|
| Average illuminance    | Large room with several luminaires and uncertain task locations                                                                                   | 1                                 |
| Illuminance at a point | Localized, known task locations, accent lighting, or evaluation of lighting system uniformity                                                     | 2 (point)<br>3 (line)<br>4 (area) |
| Average exitance       | When interreflections are critical to the illuminance calculations above (exitance is the fundamental quantity for calculating diffuse luminance) | 5                                 |
| Exitance at a point    | Calculation of luminance, contrast, or luminance ratios at                                                                                        | 6                                 |

\*1: Lumen method for average illuminance in a room with partitions. 2: Parking lot lighting. 3: Lighting a chalkboard in a classroom. 4: Diffuse skylight illuminating a desk. 5: Interreflections from daylight. 6: Luminances produced by a point source for task lighting at a desk. 7: Evaluating contrast produced on printed material.

**Figure 9-40.** Example Calculations and Their Applications

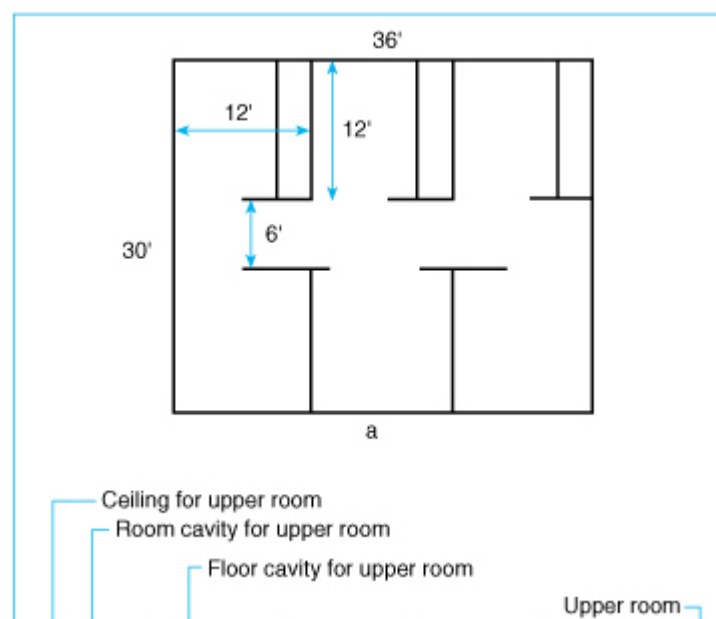
### Example 1: Lumen Method for Average Illuminance

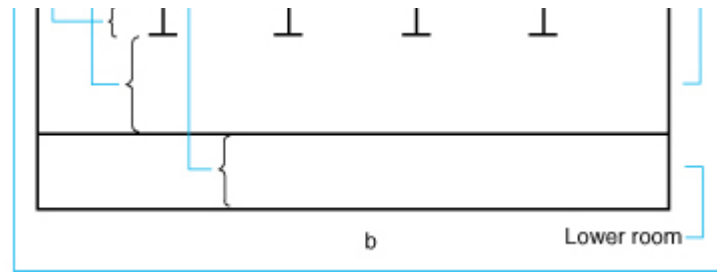
The setting for this example is a small open plan office with six workstations formed by partitions. VDTs are used extensively in this space. The office measures  $36 \times 30$  ft with a 9.5-ft floor-to-ceiling height. The partitions are 5 ft high, and each workstation is  $12 \times 12$  ft. The layout of the partitions and desks is shown in [Figure 9-41a](#). The section showing the room cavities to be used is in [Figure 9-41b](#).

**1. Determine the Quantity to be Calculated.** It is decided that an indirect lighting system is used in the space, with the goal of providing a maintained illuminance of 40 fc on the horizontal desk surfaces, which are 2.5 ft above the floor. High-angle light control is needed to suit VDT use in the space. The number of luminaires required to produce this illuminance on the desktops inside the partitioned workstations is the quantity to be calculated.

**2. Identify Luminaires and the Information Describing Them.** An indirect luminaire is used. The luminaire uses single in-line T-8 fluorescent lamps (lamp lumens = 2900 lm) and is available in continuous lengths that are multiples of 4 ft, up to a maximum length of 24 ft. A 1.5-ft pendant length is recommended by the manufacturer. Photometric data include the CUs that are shown in [Figure 9-42](#).

**3. Determine the Accuracy, Complexity, and Detail of the Calculation.** The lumen method is used to determine the number of luminaires required, and the following light loss factors are defined: luminaire dirt depreciation factor, lamp lumen depreciation factor, and ballast factor. Other light loss factors are assumed to have a value of 1.0 for this example.





**Figure 9-41.** Open plan office for example 1: (a) layout, (b) section.

| RCR | $\rho_{\text{floor}} = 20$   |    |    |    |    |    |    |    |
|-----|------------------------------|----|----|----|----|----|----|----|
|     | $\rho_{\text{ceiling}} = 80$ |    |    | 70 |    |    | 50 |    |
|     | $\rho_{\text{wall}} = 70$    | 50 | 30 | 70 | 50 | 30 | 50 | 30 |
| 0   | 75                           | 75 | 75 | 73 | 73 | 73 | 70 | 70 |
| 1   | 71                           | 69 | 68 | 70 | 68 | 66 | 65 | 64 |
| 2   | 67                           | 64 | 61 | 66 | 63 | 61 | 61 | 59 |
| 3   | 64                           | 59 | 56 | 62 | 58 | 55 | 57 | 54 |
| 4   | 60                           | 55 | 51 | 59 | 54 | 51 | 53 | 50 |
| 5   | 56                           | 50 | 46 | 55 | 50 | 46 | 49 | 45 |
| 6   | 53                           | 47 | 43 | 52 | 46 | 42 | 45 | 42 |
| 7   | 50                           | 43 | 39 | 49 | 43 | 39 | 42 | 38 |
| 8   | 46                           | 39 | 35 | 45 | 39 | 35 | 38 | 35 |
| 9   | 43                           | 36 | 32 | 42 | 36 | 32 | 35 | 31 |
| 10  | 40                           | 33 | 29 | 39 | 33 | 29 | 32 | 28 |

**Figure 9-42.** Coefficients of Utilization for Indirect Luminaire Used in Example 1

The following calculation strategy is used to take account of the light losses and shadowing produced by the partitions:

- An individual partitioned workstation is treated as a small room.
- An imaginary horizontal plane at the level of the top of the partitions represents the ceiling of an individual workstation. The partitions form the walls of this workstation, and the actual working plane is considered as the floor in the calculations. The ceiling reflectance is the effective cavity reflectance of the upper portion of the room, and the floor reflectance is the surface-area-weighted average of the desktop reflectance and effective cavity reflectance of the surfaces below the workplane. In both cases, the effective cavity reflectance is considered from a viewpoint between the workstation ceiling plane and the workplane.
- The required illuminance on the desk surface is produced if, taking account of interreflections within the workstation, sufficient light crosses the workstation ceiling plane. This light is directed onto the ceiling plane from the portion of the room above the partitions.
- Light crossing the workstation ceiling plane can be characterized both as an exitance from a viewpoint inside the workstation and as an illuminance from a viewpoint above the workstation ceiling plane. It is assumed that the distribution of the light crossing the workstation ceiling plane is diffuse.
- For the purpose of lumen calculations within the workstation, the workstation ceiling plane can be considered a perfectly diffuse luminaire. Thus, the coefficients of utilization of a perfectly diffuse emitter can be used.



f) Working back from the illuminance required on the desk, the luminous output of the diffuse luminaire (that is, the diffuse exitance of the workstation ceiling plane) is calculated.

g) This exitance is numerically equal to the illuminance that must be produced by the upper part of the room onto the workstation ceiling plane. That is, the workstation ceiling plane can be considered the floor of the upper part of the room with a required illuminance. It has a reflectance that is the effective cavity reflectance of the partitioned workstation.

h) The lumen method is applied to the space above the partitions to determine the number of indirect luminaires required to produce this illuminance. Coefficients of utilization for the indirect luminaire are used for this calculation.

**4. Identify Required Geometric, Reflectance, and Ancillary Data.** The diffuse reflectances of the room surfaces are as follows:

|            |      |
|------------|------|
| Floor      | 0.25 |
| Walls      | 0.60 |
| Ceiling    | 0.80 |
| Partitions | 0.65 |
| Desktops   | 0.35 |

It is assumed that the fluorescent lighting system operates continuously through the working day, corresponding to 10 h of operation per start. A maintenance schedule whereby lamps and luminaires are cleaned every year is also assumed.

The luminaire dirt depreciation light loss factor is determined following the procedure given in [Figure 9-14](#). Since the luminaire has an opaque bottom surface and no top enclosure, it is in maintenance category VI. Using the method given in [Figure 9-15](#), the operating atmosphere must be classified, and for this situation is determined to be clean. The luminaire dirt depreciation light loss factor is then determined from [Figure 9-17](#), and the depreciation curve for luminaires operating in a clean atmosphere. For a yearly maintenance cycle, the luminaire dirt depreciation factor is determined to be 0.85.

A more accurate determination can be made by referring to manufacturer's data for the specific lamp type to be used. Allowance can be made for the assumption that the lamps are operated for 10 h per start. The data in [Chapter 6](#) are based on 3 h per start; thus it is assumed that the lamp lumen depreciation factor should be slightly adjusted to 0.88.

The ballast factor for the magnetic ballasts used in this luminaire is 0.95. The total light loss factor (LLF) is thus  $LLF = 0.85 \times 0.88 \times 0.95 = 0.711$ .

**5. Determine Appropriate Equations.** From Equation 9-50, the lumen method equation for determining the required number of luminaires is

$$\text{number of luminaires} = \frac{E_{\text{maintained}} \times \text{workplane area}}{\text{lamps per luminaire} \times \text{lamp lumens} \times CU \times LLF}$$

**6. Solve the Equations.** The lumen method is applied first to a workstation. The CU is

**6. Solve the Equations.** The lumen method is applied first to a workstation. The CU is determined from the room cavity ratio (RCR) and the surface reflectances (determined as shown in the section "Average Illuminance Calculation: The Lumen Method"):

$$RCR = \frac{5 h (l + w)}{l \times w}$$

where  $h$  is the cavity height,  $l$  is the cavity length, and  $w$  is the cavity width. Because the ceiling of a workstation is at the level of the top of the partitions and the floor is at workplane level, the cavity height is  $5 - 2.5 - 2.5$  ft. This value and the workstation dimensions give

$$RCR = \frac{5 \times 2.5 \times (12 + 12)}{12 \times 12} = 2.08$$

Below the workplane level is a floor cavity, for which the effective cavity reflectance must be determined. It has a base reflectance of 0.25 (the actual floor) and a wall reflectance of 0.60, and the floor cavity ratio (FCR) is given by

$$FCR = \frac{5 \times 2.5 \times (12 + 12)}{12 \times 12} = 2.08$$

Figure 9-27 is read to determine the effective floor cavity reflectance ( $\rho_{FC}$ ), using the floor cavity ratio 2.08 and the reflectances 0.25 and 0.60. By linear interpolation, the result is  $\rho_{FC} = 0.23$ .

In an area as small as the workstation, the size of the desk is significant. A surface-area-weighted average reflectance ( $\rho_{FCave}$ ) can be determined for the floor or base of the cavity as shown in Equation 9-58. For the present case,

$$\rho_{FCave} = \frac{A_{FC} \rho_{FC} + A_{DT} \rho_{DT}}{A_{FC} + A_{DT}}$$

where the subscript  $DT$  indicates the desktop.  $A_{FC}$  and  $A_{DT}$  indicate the areas of the floor and desktop, respectively. If the area of the desktop is  $18 \text{ ft}^2$ , the effective floor cavity reflectance is

$$\rho_{FCave} = \frac{(12 \times 12 - 18) \times 0.23 + 18 \times 0.35}{(12 \times 12 - 18) + 18} = 0.245$$

The reflectance assigned to the workstation ceiling plane is the effective cavity reflectance of the upper portion of the room from a viewpoint inside the workstation. Because the room height is 9.5 ft and the partitions are 5 ft tall, the cavity height is 4.5 ft. The ceiling cavity ratio (CCR) is given by

$$CCR = \frac{5 \times 4.5 \times (36 + 30)}{36 \times 30} = 1.37$$

The base reflectance of this cavity is the ceiling reflectance of the room, 0.80, and the wall reflectance is the wall reflectance of the room, 0.60. Referring to [Figure 9-27](#), the effective ceiling cavity reflectance for the workspace is 0.65.

Thus, the parameters for determining the CU in the workstation are  $RCR = 2.08$ ,  $\rho_{\text{ceiling}} = 0.65$ ,  $\rho_{\text{walls}} = 0.60$ , and  $\rho_{FC\text{ave}} = 0.245$ . A CU table for a perfectly diffuse emitter is given in [Figure 9-30](#). Linear interpolation gives the value  $CU = 0.80$ .

As stated in the CU table, all values assume a floor cavity reflectance of 0.20. Thus in this situation the CU value must be modified to take account of the high floor cavity reflectance. The multiplier for this purpose is interpolated from the table of multipliers in [Figure 9-29](#). For  $\rho_{FC\text{ave}} = 0.245$ , the result is multiplier = 1.06, and so  $CU = 0.80 \times 1.06 = 0.85$ .

From the lumen method equation, the number of lumens required to pass through the workstation ceiling plane is

$$\begin{aligned} \text{lumens required} &= \\ \frac{E_{\text{maintained}} \times \text{workplane area}}{CU} &= \frac{(40 \times 12 \times 12)}{0.85} = 6776 \text{ lm} \end{aligned}$$

The illuminance that must be produced on this plane is thus

$$E_{\text{required}} = \frac{\text{required lumens}}{\text{area of workstation}} = \frac{6776}{(12 \times 12)} = 47 \text{ fc}$$

The lumen method is now applied to the upper portion of the room. The room cavity height is the distance between the partition tops and suspended luminaires, 3 ft. The RCR is

$$RCR = \frac{5 \times 3 \times (36 + 30)}{36 \times 30} = 0.916$$

Since the luminaires are suspended, an effective ceiling cavity reflectance must be determined. The CCR is

$$CCR = \frac{5 \times 1.5 \times (36 + 30)}{36 \times 30} = 0.458.$$

The base reflectance of this cavity is the room ceiling reflectance, 0.80, and the wall reflectance is the room wall reflectance, 0.60. Referring to [Figure 9-27](#), the effective ceiling cavity reflectance is  $\rho_{CC} = 0.74$ .

The effective floor reflectance of the room is determined from the data on the workstations. The effective reflectance of the workplane has been calculated to be 0.245, and this plane forms the cavity base. The partitions, having a reflectance of 0.65, form the cavity walls. The cavity height is the height between the workplane and the workstation ceiling plane, 2.5 ft. The cavity ratio is

$$CR = \frac{5 \times 25 \times (12 + 12)}{12 \times 12} = 2.08.$$

Referring again to [Figure 9-27](#), the effective floor cavity reflectance is  $\rho_{FC} = 0.24$ .

Thus, the parameters for determining the CU are  $RCR = 0.916$ ,  $\rho_{CC} = 0.74$ ,  $\rho_{walls} = 0.60$ , and  $\rho_{FC} = 0.24$ . Interpolation in the CU table for the indirect luminaire ([Figure 9-42](#)) gives  $CU = 0.67$ . As previously, a multiplier must be determined to correct for the difference between the assumed floor reflectance of 0.20 and the value 0.24. From [Figure 9-29](#), the result is  $\text{Multiplier} = 1.08$ . Thus the corrected coefficient of utilization is  $CU = 0.67 \times 1.08 = 0.72$ .

The other parameters for the lumen method equation are lamps per luminaire = 1 and lamp lumens = 2900 lm.

Finally, the number of luminaires is

$$\begin{aligned} \text{number of luminaires} &= \frac{E_{\text{maintained}} \times \text{workplane area}}{\text{lamps per luminaire} \times \text{lamp lumens} \times CU \times LLF} \\ &= \frac{47 \times 36 \times 30}{1 \times 2900 \times 0.72 \times 0.771} = 31.5 \end{aligned}$$

An architecturally practical layout of these luminaires would involve 32 luminaires. One such arrangement is four rows, each 32 ft long, consisting of eight luminaires per row.

## Example 2: Lighting a Small Parking Area

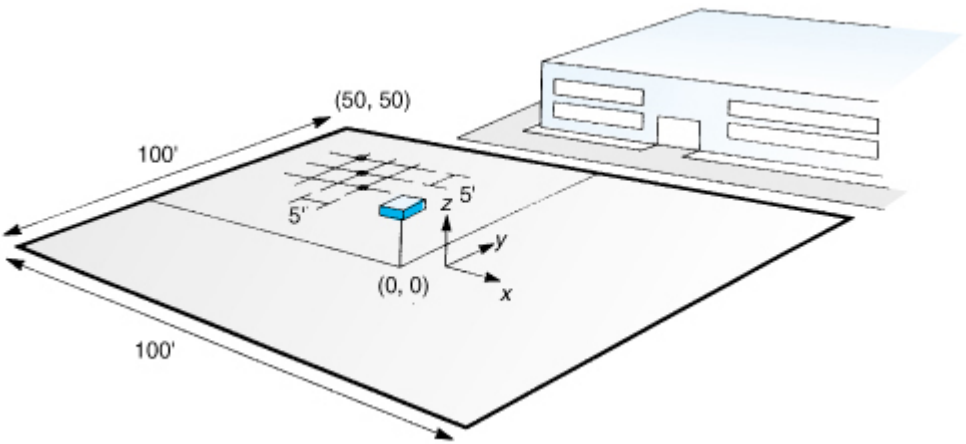
The setting for this example is a small parking lot near an office building. The parking lot measures  $100 \times 100$  ft and is adjacent to a three-story office building. It is desired to keep the equipment height consistent with the architectural scale of the building. An analysis is to be performed to see if a single luminaire on a pole can sufficiently illuminate the entire parking lot. The pole is placed at the center of the area.

**1. Determine the Quantity to be Calculated.** A diagram of the parking area and the proposed lighting system appears in [Figure 9-43](#). To evaluate the effectiveness of a single pole location, the illuminances are calculated at the points of a  $5 \times 5$ -ft rectangular grid on the pavement surface.

This analysis is performed with three typical pole heights: 15, 20, and 25 ft. The evaluation criterion is the illuminance recommendation (see [Chapter 22](#), Roadway Lighting) for a low-activity-level, open parking facility: a minimum horizontal illuminance of 0.2 fc, minimum vertical illuminance of 0.1 fc, and a uniformity criterion that the ratio of maximum to minimum illuminance is to be no greater than 20:1.

**2. Identify Luminaires and the Information Describing Them.** The luminaire to be used in the analysis is Type VS with a square distribution, using a 250-W clear metal halide lamp, and having a lumen rating of 20 500 lm. Photometric data are available and are shown in [Figure 9-44](#).

having a lumen rating of 20,000 lm. Photometric data are available and are shown in [Figure 9-44](#) as they might appear in a photometric report.



**Figure 9-43.** Diagram of parking area for Example 2.

**3. Determine the Accuracy, Complexity, and Detail of the Calculation.** Initial calculations are performed at the points along the diagonal of this grid. It is anticipated that the illuminance is likely to be lowest at the corners of the parking area because the distance from the luminaires is greatest at the corners.

**4. Identify Required Geometric, Reflectance, and Ancillary Data.** The necessary dimensions are shown in [Figure 9-43](#). On their photometric reports, manufacturers often recommend a total light loss factor to be used with their luminaires. In this case, the manufacturer recommended a total light loss factor of 0.85. Reflectances are unimportant, since this is an outdoor application.

| Vertical Angle | Intensity (cd) at Lateral Angle |      |      |      |      |      |      |      |      |
|----------------|---------------------------------|------|------|------|------|------|------|------|------|
|                | 0°                              | 5°   | 15°  | 25°  | 35°  | 45°  | 55°  | 65°  | 75°  |
| 0.0°           | 2886                            | 2886 | 2886 | 2886 | 2886 | 2886 | 2886 | 2886 | 2886 |
| 2.5°           | 2879                            | 2887 | 2887 | 2904 | 2921 | 2929 | 2946 | 2954 | 2954 |
| 5.0°           | 2846                            | 2854 | 2879 | 2904 | 2921 | 2938 | 2946 | 2963 | 2963 |
| 7.5°           | 2829                            | 2829 | 2862 | 2879 | 2896 | 2896 | 2904 | 2912 | 2921 |
| 10.0°          | 2779                            | 2795 | 2812 | 2820 | 2829 | 2837 | 2854 | 2854 | 2879 |
| 12.5°          | 2745                            | 2745 | 2762 | 2779 | 2779 | 2795 | 2812 | 2837 | 2846 |
| 15.0°          | 2678                            | 2678 | 2695 | 2728 | 2753 | 2762 | 2787 | 2812 | 2820 |
| 17.5°          | 2628                            | 2628 | 2645 | 2678 | 2712 | 2737 | 2770 | 2795 | 2812 |
| 20.0°          | 2578                            | 2578 | 2603 | 2636 | 2670 | 2712 | 2779 | 2837 | 2854 |
| 22.5°          | 2561                            | 2553 | 2553 | 2611 | 2653 | 2728 | 2812 | 2904 | 2921 |
| 25.0°          | 2544                            | 2553 | 2544 | 2628 | 2703 | 2753 | 2804 | 2879 | 2879 |
| 27.5°          | 2461                            | 2477 | 2511 | 2620 | 2720 | 2770 | 2829 | 2896 | 2887 |
| 30.0°          | 2427                            | 2435 | 2461 | 2611 | 2720 | 2812 | 2904 | 3021 | 2963 |
| 32.5°          | 2578                            | 2569 | 2494 | 2728 | 2779 | 2904 | 3046 | 3155 | 3021 |
| 35.0°          | 2712                            | 2678 | 2561 | 2929 | 2896 | 3080 | 3297 | 3356 | 3138 |
| 37.5°          | 3046                            | 2921 | 2653 | 3122 | 3063 | 3406 | 3599 | 3691 | 3373 |
| 40.0°          | 3565                            | 3331 | 2912 | 3456 | 3389 | 4051 | 3967 | 4268 | 3590 |
| 42.5°          | 3733                            | 3456 | 3122 | 3892 | 3825 | 4695 | 4293 | 4670 | 3749 |
| 45.0°          | 4118                            | 3599 | 3189 | 4067 | 4101 | 5030 | 4729 | 4812 | 3984 |
| 47.5°          | 4185                            | 3841 | 3297 | 4469 | 4377 | 5097 | 4896 | 5214 | 4101 |
| 50.0°          | 3749                            | 3565 | 3482 | 4570 | 4494 | 5038 | 4871 | 5381 | 4101 |
| 52.5°          | 3314                            | 3097 | 3465 | 4327 | 4243 | 4829 | 4645 | 5281 | 4385 |
| 55.0°          | 3046                            | 3097 | 3758 | 3992 | 4093 | 5088 | 4888 | 5842 | 5139 |
| 57.5°          | 2142                            | 2544 | 3130 | 4084 | 5088 | 6955 | 5716 | 5591 | 4553 |
| 60.0°          | 1741                            | 2134 | 2410 | 3281 | 4461 | 5323 | 4385 | 4143 | 3808 |

|       |      |      |      |      |      |      |      |      |      |
|-------|------|------|------|------|------|------|------|------|------|
| 62.5° | 1490 | 1942 | 2260 | 2820 | 4076 | 4235 | 3716 | 3348 | 3908 |
| 65.0° | 1205 | 1657 | 2402 | 2293 | 3724 | 3515 | 3540 | 3389 | 3858 |
| 67.5° | 1038 | 1398 | 2193 | 2151 | 3574 | 4009 | 4452 | 3816 | 4921 |
| 70.0° | 836  | 1105 | 1774 | 1967 | 3565 | 4645 | 5189 | 4093 | 4720 |
| 72.5° | 619  | 795  | 1205 | 1758 | 2753 | 3657 | 4185 | 3607 | 3549 |
| 75.0° | 418  | 460  | 518  | 1138 | 2025 | 3021 | 3063 | 1891 | 2092 |
| 77.5° | 234  | 192  | 200  | 309  | 535  | 1029 | 1071 | 594  | 493  |
| 80.0° | 117  | 100  | 108  | 142  | 175  | 184  | 209  | 167  | 108  |
| 82.5° | 50   | 58   | 50   | 50   | 58   | 66   | 50   | 50   | 41   |
| 85.0° | 33   | 16   | 41   | 16   | 25   | 16   | 16   | 16   | 16   |
| 87.5° | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| 90.0° | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |

\*Total lumen output is 20,500 lm.

**Figure 9-44.** Parking Lot Luminaire Luminous Intensity Distribution for Type A Photometry\*

**5. Determine Appropriate Equations.** The smallest mounting height to be used is 15 ft, which is more than 5 times the largest dimension of the luminaire. Thus, the five-times rule is satisfied for any point on the calculation grid, and the luminaire can be treated as a point source. The inverse square cosine law can be used for illuminance computations:

$$E = \frac{I(\theta, \psi) \cos \theta}{D^2}$$

The geometry of this problem allows each of the trigonometric and distance quantities in this equation to be expressed in rectangular coordinates ([Figure 9-43](#)):

$$\theta = \arctan \left( \frac{\sqrt{x^2 + y^2}}{z} \right)$$

$$\psi = \arctan \left( \frac{x}{y} \right)$$

$$\cos \xi = \frac{z}{\sqrt{x^2 + y^2 + z^2}}$$

$$D^2 = x^2 + y^2 + z^2$$

These combine to give the following expression for the horizontal and vertical illuminances,  $E_H$  and  $E_V$ , respectively:

$$E_H = I(\theta, \psi) \frac{z}{(x^2 + y^2 + z^2) \sqrt{x^2 + y^2 + z^2}}$$

$$E_V = I(\theta, \psi) \frac{y}{(x^2 + y^2 + z^2) \sqrt{x^2 + y^2 + z^2}}$$

**6. Solve the Equations** An analysis is performed at the grid points along a diagonal. Referring

**Solve the Equations.** An analysis is performed at the grid points along a diagonal. Referring to [Figure 9-43](#), the rectangular coordinates can be determined with respect to the luminaire. Three values of  $z$  are used for each pair of  $x$  and  $y$  coordinates, each value of  $z$  representing one of the three pole heights to be evaluated. The point ( $x = 0, y = 0$ ) is directly underneath the luminaire. The point ( $x = 50, y = 50$ ) is at the corner of the parking lot. The luminous intensity values are obtained by linear interpolation from [Figure 9-44](#).

The intensity at ( $\theta = 43.3^\circ, \psi = 45.0^\circ$ ) is estimated as 3801 cd. The results of all intermediate calculations are summarized in [Figure 9-45](#). The horizontal and vertical illuminance at each position is calculated for each of the three pole heights.

At a distance of 50 ft, the horizontal illuminance near the corner of the lot is below 0.2 fc for a pole height of 15 or 20 ft. Only for a pole height of 25 ft is the minimum illuminance requirement of 0.2 fc met over the entire parking lot. This pole height also minimizes the maximum-to-minimum illuminance ratio over the parking area, which meets the required maximum ratio of 20:1 from [Chapter 22](#), Roadway Lighting, as demonstrated below. Additionally, the 25-ft pole height produced a minimum vertical illuminance of 0.26 fc, which meets the minimum requirement.

The maximum-to-minimum ratio for the pole height of 25 ft is calculated as follows:

$$\frac{\text{maximum illuminance}}{\text{minimum illuminance}} = \frac{4.54 \text{ fc}}{0.23 \text{ fc}} = \frac{19.7}{1}$$

Thus the ratio is 19.7:1, which meets IESNA recommendations for uniformity.

### Example 3: Calculation of Illuminance at a Point: Direct and Interreflected Components

This example concerns lighting a chalkboard.

| $x$ (ft) | $y$ (ft) | $z$ (ft) | $\theta$ | $\psi$ | $I$ (cd) | $D$ (ft) | $E$ (fc) |
|----------|----------|----------|----------|--------|----------|----------|----------|
| 0.0      | 0.0      | 15.0     | 0.0°     | 0.0°   | 2885     | 15.0     | 12.83    |
| 0.0      | 0.0      | 20.0     | 0.0°     | 0.0°   | 2886     | 20.0     | 7.22     |
| 0.0      | 0.0      | 25.0     | 0.0°     | 0.0°   | 2886     | 25.0     | 4.62     |
| 5.0      | 5.0      | 15.0     | 25.2°    | 45.0°  | 2754     | 16.6     | 9.03     |
| 5.0      | 5.0      | 20.0     | 19.5°    | 45.0°  | 2717     | 21.2     | 5.70     |
| 5.0      | 5.0      | 25.0     | 15.8°    | 45.0°  | 2754     | 26.0     | 3.92     |
| 10.0     | 10.0     | 15.0     | 43.3°    | 45.0°  | 4802     | 20.6     | 8.23     |
| 10.0     | 10.0     | 20.0     | 35.3°    | 45.0°  | 3119     | 24.5     | 4.24     |
| 10.0     | 10.0     | 25.0     | 29.5°    | 45.0°  | 2804     | 28.7     | 2.96     |
| 15.0     | 15.0     | 15.0     | 54.7°    | 45.0°  | 5057     | 26.0     | 4.32     |
| 15.0     | 15.0     | 20.0     | 46.7°    | 45.0°  | 5076     | 29.2     | 4.08     |
| 15.0     | 15.0     | 25.0     | 40.3°    | 45.0°  | 4128     | 32.8     | 2.92     |
| 20.0     | 20.0     | 15.0     | 62.1°    | 45.0°  | 4409     | 32.0     | 2.02     |
| 20.0     | 20.0     | 20.0     | 54.7°    | 45.0°  | 5057     | 34.6     | 2.44     |
| 20.0     | 20.0     | 25.0     | 48.5°    | 45.0°  | 5073     | 37.7     | 2.37     |
| 25.0     | 25.0     | 15.0     | 67.0°    | 45.0°  | 3910     | 38.4     | 1.04     |
| 25.0     | 25.0     | 20.0     | 60.5°    | 45.0°  | 5105     | 40.6     | 1.53     |
| 25.0     | 25.0     | 25.0     | 54.7°    | 45.0°  | 5057     | 43.3     | 1.56     |
| 30.0     | 30.0     | 15.0     | 70.5°    | 45.0°  | 4147     | 45.0     | 0.68     |
| 30.0     | 30.0     | 20.0     | 64.8°    | 45.0°  | 3573     | 46.9     | 0.69     |
| 30.0     | 30.0     | 25.0     | 59.5°    | 45.0°  | 5649     | 49.2     | 1.19     |
| 35.0     | 35.0     | 15.0     | 73.1°    | 45.0°  | 3504     | 51.7     | 0.38     |

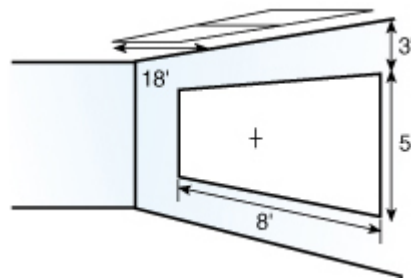


|      |      |      |       |       |      |      |      |
|------|------|------|-------|-------|------|------|------|
| 35.0 | 35.0 | 20.0 | 68.0° | 45.0° | 4136 | 53.4 | 0.54 |
| 35.0 | 35.0 | 25.0 | 63.2° | 45.0° | 4437 | 55.5 | 0.65 |
| 40.0 | 40.0 | 15.0 | 75.1° | 45.0° | 2941 | 58.5 | 0.22 |
| 40.0 | 40.0 | 20.0 | 70.5° | 45.0° | 4147 | 60.0 | 0.38 |
| 40.0 | 40.0 | 25.0 | 66.2° | 45.0° | 3752 | 61.8 | 0.40 |
| 45.0 | 45.0 | 15.0 | 76.7° | 45.0° | 1666 | 65.4 | 0.09 |
| 45.0 | 45.0 | 20.0 | 72.6° | 45.0° | 3632 | 66.7 | 0.24 |
| 45.0 | 45.0 | 25.0 | 68.6° | 45.0° | 4289 | 68.4 | 0.34 |
| 50.0 | 50.0 | 15.0 | 78.0° | 45.0° | 860  | 72.3 | 0.03 |
| 50.0 | 50.0 | 20.0 | 74.2° | 45.0° | 3225 | 73.5 | 0.16 |
| 50.0 | 50.0 | 25.0 | 70.5° | 45.0° | 4147 | 75.0 | 0.25 |

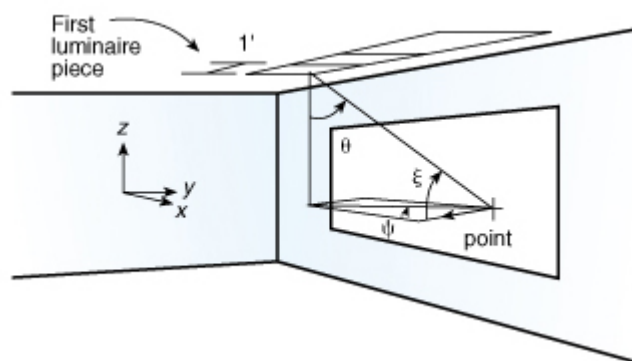
**Figure 9-45.** Intermediate Calculations for Example 2

**1. Determine the Quantity to Be Calculated.** The quantity of interest is the illuminance at a point on a chalkboard. This is used to determine if a design illuminance criterion of 20 fc on the chalkboard is met. It is assumed that the point at the center of the chalkboard is representative; this point is used for calculations. The layout is shown in [Figures 9-46](#) and 9-47.

**2. Identify Luminaires and the Information Describing Them.** A pair of 1 × 4-ft recessed troffers, each with two T-12 fluorescent lamps, are used. The total produced by a single luminaire is 3791 lm. The luminous intensity distribution for this luminaire is shown in [Figure 9-48](#) as it might appear in a photometric report.



**Figure 9-46.** Pertinent room dimensions for Example 3, lighting a chalkboard.



**Figure 9-47.** Illustration of angles and dimensions for Example 3.

**3. Determine the Accuracy, Complexity, and Detail of the Calculation.** The direct component of illuminance is calculated from the two luminaires. It is not possible to treat the luminaires as point sources because of their size and proximity to the chalkboard. Because of their shape, they are considered to be line sources. Therefore the five-times rule is used to determine the number of discrete pieces of luminaire that must be considered.



The distance  $D$  from the center of one of the luminaires to the center of the chalkboard, as can be seen in [Figures 9-46](#) and 9-47, is

$$D = \sqrt{x^2 + y^2 + z^2} = \sqrt{2^2 + 1.5^2 + 5.5^2} = 6.04 \text{ ft}$$

The five-times rule requires the dimensions of the discrete pieces of the luminaire to be no greater than  $6.04/5 = 1.2$  ft. Since the luminaires measure approximately  $1 \times 4$  ft, each can be discretized into four sections of  $1 \text{ ft}^2$  along its length. Each discrete piece of the luminaire is assumed to emit 25% of the luminaire lumens. Therefore, each has a luminous intensity distribution equal to 25% that of the entire luminaire.

The interreflected component is determined using the average interreflected illuminance over the chalkboard, since the average interreflected illuminance variation is likely to be small. It is assumed that the principal interreflection is between the chalkboard and a section of the ceiling nearby. The floor is very likely to have a low reflectance and is ignored for purposes of interreflected component calculations. Other walls are assumed to be sufficiently far from the chalkboard to give a negligible contribution to the interreflected component. Note that luminaires in the room other than those used to directly light the chalkboard may also produce direct and interreflected illuminance on the chalkboard. Other sources of illumination are not considered in this example.

| Angle<br>$\theta$ | Intensity (cd)             |                   |                              |
|-------------------|----------------------------|-------------------|------------------------------|
|                   | Along ( $\psi = 0^\circ$ ) | $\psi = 45^\circ$ | Across ( $\psi = 90^\circ$ ) |
| 0°                | 1531                       | 1531              | 1531                         |
| 5°                | 1440                       | 1554              | 1547                         |
| 15°               | 1357                       | 1495              | 1523                         |
| 25°               | 1238                       | 1401              | 1519                         |
| 35°               | 1072                       | 1331              | 1652                         |
| 45°               | 852                        | 1242              | 1259                         |
| 55°               | 586                        | 771               | 612                          |
| 65°               | 155                        | 205               | 216                          |
| 75°               | 26                         | 31                | 26                           |
| 85°               | 4                          | 13                | 9                            |
| 90°               | 0                          | 0                 | 0                            |

**Figure 9-48.** Luminous Intensity Distribution for Schoolroom Luminaire

**4. Identify Required Geometric, Reflectance, and Ancillary Data.** The chalkboard reflectance  $\rho_1$  is 0.25. The ceiling reflectance  $\rho_2$  is 0.80. The pertinent room dimensions are as shown in [Figure 9-46](#).

**5. Determine Appropriate Equations**

*Direct Component.* The discrete luminaire pieces are small enough for the inverse square cosine law to be applied for each of the eight pieces (two four-foot luminaires, each divided into one-foot sections), and the illuminances (calculated using Equation 9-4) added together to give the total illuminance:

$$E = \sum_{i=1}^n \frac{I_i \cos \xi_i}{D_i^2}$$

where

$I_i$  = intensity of the  $i$ th piece in the direction to the center of the chalkboard,

$\xi_i$  = angle between the normal to the chalkboard surface and a line from the  $i$ th piece to the center of the chalkboard,

$D_i$  = distance between the center of the chalkboard and the  $i$ th piece.

*Interreflected Component.* A general equation for interreflected illuminance between two diffuse surfaces is used, based on Equation 9-23a:

$$\bar{E}_{1 \text{ inter}} = \frac{\bar{E}_{1 \text{ dir}} + \bar{E}_{2 \text{ dir}} f_{1 \rightarrow 2}}{1 - \rho_1 \rho_2 f_{1 \rightarrow 2} f_{2 \rightarrow 1}} - \bar{E}_{1 \text{ dir}}$$

where

$\bar{E}_{1 \text{ dir}}$  = direct illuminance onto surface 1,

$\bar{E}_{2 \text{ dir}}$  = direct illuminance onto surface 2,

$f_{1 \rightarrow 2}$  = radiative exchange form factor from surface 1 to surface 2,

$f_{2 \rightarrow 1}$  = radiative exchange form factor from surface 2 to surface 1,

$\rho_1, \rho_2$  = diffuse reflectances of surfaces 1 and 2.

In the present application, surface 1 is the chalkboard and surface 2 is the ceiling near the chalkboard. In this case only the chalkboard has an initial illuminance, and the general equation becomes

$$\bar{E}_{\text{inter}} = \frac{\bar{E}_{\text{dir}}}{1 - \rho_{cb} \rho_c f_{cb \rightarrow c} f_{c \rightarrow cb}} - \bar{E}_{\text{dir}}$$

where

$\bar{E}_{\text{dir}}$  = direct illuminance on the chalkboard,

$f_{cb \rightarrow c}$  = radiative exchange form factor between the chalkboard ( $cb$ ) and the ceiling ( $c$ )

$f_{c \rightarrow cb}$  = radiative exchange form factor between the ceiling and the chalkboard,

$\rho_{cb}, \rho_c$  = diffuse reflectances of the chalkboard and ceiling.

## 6. Solve the Equations

*Direct Component.* The intermediate quantities required to calculate the direct component of illuminance are shown below and in [Figure 9-49](#):

$$D_i = \sqrt{x_i^2 + y_i^2 + z_i^2}$$

$$\theta_i = \arccos\left(\frac{z_i}{D_i}\right)$$

$$\psi_i = \arctan\left(\frac{y_i}{x_i}\right)$$

$$\cos \xi = \frac{y_i}{D_i}$$

The angle  $\psi$  is measured from the lamp axis of the luminaire. The plane of data corresponding to a value of zero for this angle is identified as "along" in [Figure 9-48](#). Intensities for angles not between 0 and 90° are obtained as discussed above. Negative angles can be converted to positive angles by adding 360°. The luminous intensities are linearly interpolated from the luminous intensity distribution data in [Figure 9-48](#) and divided by 4 because of the discretization of each luminaire into four pieces. All of the calculated values for each of the eight luminaire pieces are shown in [Figure 9-49](#). The total direct illuminance is then the sum of the partial illuminances in the column at the far right of the table, or 18.5 fc.

| Luminaire<br>Piece (i) | $x_i$ | $y_i$ | $z_i$ | $D_i$ | $\cos \xi_i$ | $\theta_i$ | $\psi_i$ | $I_i$ | $E_i$ |
|------------------------|-------|-------|-------|-------|--------------|------------|----------|-------|-------|
| 1                      | -3.5  | 1.5   | 5.5   | 6.69  | 0.224        | 34.7°      | -23.2°   | 302   | 1.51  |
| 2                      | -2.5  | 1.5   | 5.5   | 6.22  | 0.241        | 27.8°      | -31.0°   | 331   | 2.06  |
| 3                      | -1.5  | 1.5   | 5.5   | 5.89  | 0.255        | 21.0°      | -45.0°   | 360   | 2.65  |
| 4                      | -0.5  | 1.5   | 5.5   | 5.72  | 0.262        | 15.9°      | -71.6°   | 377   | 3.02  |
| 5                      | 0.5   | 1.5   | 5.5   | 5.72  | 0.262        | 15.9°      | 71.6°    | 377   | 3.02  |
| 6                      | 1.5   | 1.5   | 5.5   | 5.89  | 0.255        | 21.0°      | 45.0°    | 360   | 2.65  |
| 7                      | 2.5   | 1.5   | 5.5   | 6.22  | 0.241        | 27.8°      | 31.0°    | 331   | 2.06  |
| 8                      | 3.5   | 1.5   | 5.5   | 6.69  | 0.224        | 34.7°      | 23.2°    | 302   | 1.51  |

**Figure 9-49.** Intermediate Calculations for Example 3

*Interreflected Component.* As shown above, this calculation requires the initial average illuminance on the chalkboard. For the purpose of calculating the interreflected component, it is assumed to be the same as the average illuminance on the entire wall. This average illuminance can be calculated from (luminaire lumens incident onto the chalkboard)/(area of the chalkboard wall). The luminaires have intensity distributions that are symmetric both along and across the lamp axis and are mounted close to the chalkboard wall. Thus it can be assumed that approximately 50% of the luminaire lumens reach this surface directly. For each luminaire, 50% of 3791, or 1895.5 lm, reaches the chalkboard wall directly. Because there are two luminaires, the total flux incident on the chalkboard wall is assumed to be 3791 lm. The area of the chalkboard wall is 64 ft<sup>2</sup> (8 × 8 ft). Therefore,

$$\bar{E}_{\text{dir}} = \frac{\text{incident flux}}{\text{area}} = \frac{3791 \text{ lm}}{64 \text{ ft}^2} = 59 \text{ fc}$$

Solving for the interreflected illuminance component gives

$$\bar{E} = \bar{E}_{\text{dir}} + \bar{E}_{\text{refl}}$$

$$E_{\text{inter}} = 1 - \rho_{cb} \rho_c f_{cb \rightarrow c} f_{c \rightarrow cb} = E_{\text{dir}}$$

where  $E_{\text{dir}}$ ,  $\rho_{cb}$ , and  $\rho_c$  have been previously defined, and  $f_{cb \rightarrow c}$  and  $f_{c \rightarrow cb}$  are both assumed to equal 0.2. Hence  $E_{\text{inter}} = 0.5 \text{ fc}$ . The total illuminance at the point is then  $E = E_{\text{dir}} + E_{\text{inter}} = 18.5 \text{ fc} + 0.5 \text{ fc} = 19 \text{ fc}$ .

Given the accuracy of the equations used (which is no better than 5%, as discussed in the description of the algorithm above), the calculated illuminance of 19 fc may or may not meet the established design criterion of 20 fc. Further analysis on the part of the designer is probably necessary in this borderline case.

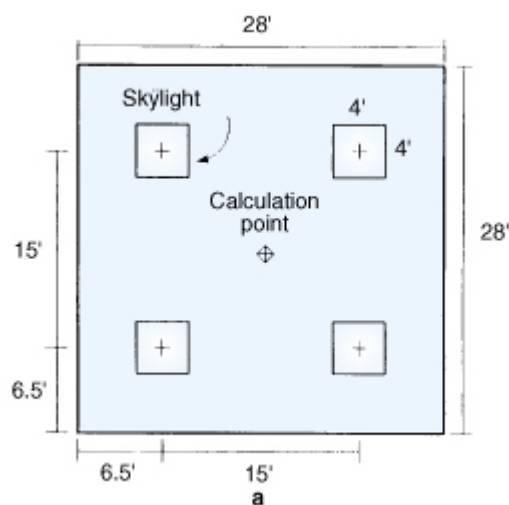
Note that the interreflected component is significantly smaller than the direct component. Because of this, a more elaborate calculation of the interreflected component produced by these luminaires is not required.

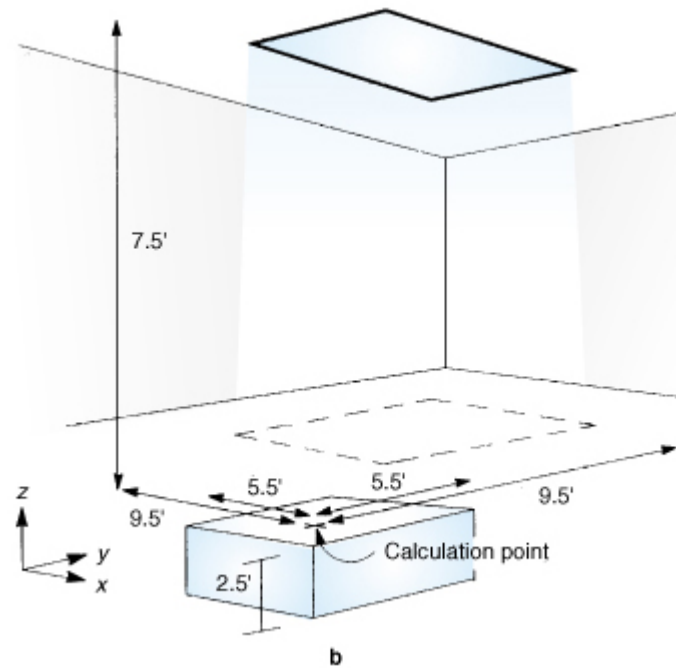
#### Example 4: Calculation of Illuminance at a Point from an Area Source: Direct Component Only

This example addresses skylights in a small classroom in Denver, Colorado.

**1. Determine the Quantity to Be Calculated.** The quantity of interest is the direct component of illuminance at a point on a desk in a small classroom. The calculation point is at the center of the room on a desk 2.5 ft high. The room is  $28 \times 28$  ft with a floor-to-ceiling height of 10 ft. It has a ceiling reflectance of 0.80, a wall reflectance of 0.46, and a floor reflectance of 0.20.

**2. Identify Sources and the Information Describing Them.** The room is lighted by an array of four domed skylights, as shown in [Figure 9-50](#). Each skylight is made of plastic that exhibits a diffuse transmittance of 0.15 for light incident perpendicular to the surface. For light incident at other angles, the transmittance is diffuse but the value is reduced. This diffuse directional transmittance is given by the equation  $T(\theta) = 0.15 \cos^2 \theta$ , where  $\theta$  is the angle of incidence. This equation is used for the direct solar contribution. The total diffuse transmittance  $T$  for light incident equally from all directions is 0.10.





**Figure 9-50.** Classroom and skylights for Examples 4 and 5: (a) plan, (b) perspective.

**3. Determine the Accuracy and Complexity.** The direct component is calculated from the skylights, assuming that they are diffuse area sources. The equation for the illuminance produced by a diffuse area source is used (Equation 9-9). This equation requires the source exitance, which in this case is the skylight exitance. This exitance is produced by sunlight and sky light transmitted through the dome of the skylight.

Since the skylight is domed, the transmittance is almost independent of the direction from which the light arrives onto the skylight. This would not be true if the skylight were flat. Domed skylights exhibit a transmittance change due to the thinning of material at the top of the dome. The effect of domed skylights is determined by evaluating the change in transmittance.

The illuminance produced by the skylights is a function of their exitance, which in turn is a function of the daylight illuminance on them and their transmittance. Both of these quantities are affected by the sun's position. Thus the calculation must be made for a specific date, time, and sky condition as described in [Chapter 8, Daylighting](#).

The calculation for the interreflected component is shown in example 5.

**4. Identify Required Geometric, Reflectance, and Ancillary Data.** The date and time of the example calculation is April 10, 12 noon for Denver, Colorado. The sky condition is assumed to be clear. The available horizontal illuminance, as calculated according to the method described in [Chapter 8, Daylighting](#), is  $E_{\text{sun}} = 9150 \text{ fc}$  and  $E_{\text{sky}} = 1400 \text{ fc}$ . The solar altitude for these conditions is  $57.5^\circ$ , so the sun is  $32.5^\circ$  from the zenith.

**5. Determine Appropriate Equations.** The equation for the illuminance produced by a diffuse area source is  $E = Mc$ , where  $M$  is the diffuse exitance of the source and  $c$  is the configuration factor for the area to the point. In this case the configuration factor is for a rectangle to a point in a plane parallel to the plane of the rectangle. The general equation, from [Figure 9-3](#), is:

$$c = \frac{1}{2\pi} \sum_{i=1}^2 \sum_{j=1}^2 F(x_i, y_j) (-1)^{i+j}$$

$$i = 1, j = 1$$

where

$$F(x_i, y_j) = \frac{x_i}{\sqrt{x_i^2 + z^2}} \arctan \left( \frac{y_j}{\sqrt{x_i^2 + z^2}} \right) + \frac{y_j}{\sqrt{y_j^2 + z^2}} \arctan \left( \frac{x_i}{\sqrt{y_j^2 + z^2}} \right)$$

$x_i$  = distance from the calculation point to the  $i$ th edge of the rectangular source in the  $x$  direction,

$y_j$  = distance from the calculation point to the  $j$ th edge of the rectangular source in the  $y$  direction,

$z$  = distance between the plane containing the calculation point and the plane of the source.

Since there is more than one diffuse area source, the total direct component of illuminance is

$$E = \sum_{i=1}^4 M_i c_i$$

All four skylights have the same transmittance characteristics, and their proximity means that they have the same sky and sun illuminance. Thus they exhibit the same exitance. This gives

$$E = M \sum_{i=1}^4 c_i$$

In the present example, the calculation point is at the center of the room and is thus symmetrically placed with respect to the skylights, and the four configuration factors are the same. The illuminance is then  $E = 4Mc$ .

The exitance  $M$  of the skylight within the room is

$$M = E_{\text{sun}} T_{\text{net}} + E_{\text{sky}} T$$

where

$E_{\text{sun}}$  = horizontal illuminance produced by the sun,

$E_{\text{sky}}$  = horizontal illuminance produced by the sky,

$T_{\text{net}}$  = net directional transmittance of the skylight,

$T$  = transmittance of the skylight glass.

$T'$  = total diffuse transmittance of the skylight.

The equation for the net directional transmittance  $T_{\text{net}}$  of a domed skylight for directional light (i.e., from the sun) is  $T_{\text{net}} = 1.25 T(0) [1.18 - 0.416 T(0)]$ , where  $T(0)$  is the diffuse transmittance for light incident perpendicularly to the surface of the plastic (see [Chapter 8](#), Daylighting).

**6. Solve the Equations.** The skylight net transmittance is  $T_{\text{net}} = 1.25(0.15)[1.18 - 0.416(0.15)] = 0.210$ . The skylight exitance  $M$  is  $M = (9150)(0.210) + (1400)(0.10) = 2057 \text{ lm/ft}^2$ .

The configuration factor from one of the skylights to the point is calculated from the equation shown above in step 5. The distances involved are  $x_1 = 5 \text{ ft}$ ,  $x_2 = 9.5 \text{ ft}$ ,  $y_1 = 5.5 \text{ ft}$ ,  $y_2 = 9.5 \text{ ft}$ , and  $z = 7.5 \text{ ft}$ . The resulting configuration factor  $c$  is 0.0104.

The illuminance at the calculation point from the four skylights is  $E = 4Mc = 4(2057)(0.0104) = 85.5 \text{ fc}$ . Thus, for a clear sky condition at 12 noon on April 10 in Denver, the four skylights produce a direct illuminance of 86 fc on the desk in the middle of the room.

### **Example 5: Calculation of Illuminance at a Point from an Area Source: Interreflected Component**

This example also addresses skylights in a small classroom in Denver, Colorado.

**1. Determine the Quantity to Be Calculated.** The quantity of interest is the interreflected component of illuminance at a point on a desk in a small classroom. The direct illuminance component has been calculated in Example 4 and is 86 fc. The calculation point is the same as for Example 4: at the center of the room, on a desk 2.5 ft above the floor. The room is  $28 \times 28 \text{ ft}$  with a floor-to-ceiling height of 10 ft. It has a ceiling reflectance of 0.80, a wall reflectance of 0.46, and a floor reflectance of 0.20.

**2. Identify Sources and the Information Describing Them.** The room is lighted by an array of four domed skylights, as shown in [Figure 9-50](#). The skylights are described in Example 4.

**3. Determine the Accuracy and Complexity.** The interreflected component due to the skylights is calculated assuming that they are diffuse area sources. The interreflections in the room are likely to produce uniform room surface exitances, so a simple three-surface radiative transfer model is used. That is, the ceiling and floor are each treated as separate surfaces, and the four walls are grouped together and treated as the third surface. Calculating the interreflection of light results in a single final exitance for the floor, walls, and ceiling.

The ceiling and walls are then treated as diffuse area sources, and the illuminance they produce at the calculation point is the interreflected component. The equation for the illuminance produced by a diffuse area source is used.

**4. Identify Required Geometric, Reflectance, and Ancillary Data.** The date and time of the example calculation is April 10, 12 noon for Denver, Colorado. The sky condition is assumed to be clear. The available horizontal illuminance, calculated as described in [Chapter 8](#), Daylighting, is  $E_{\text{sun}} = 9150 \text{ fc}$  and  $E_{\text{sky}} = 1400 \text{ fc}$ . The reflectance data are described above in step 1.

**5. Determine Appropriate Equations.** Equations 9-24 through 9-26 governing the interreflection of light in a three-surface model are

$$M_c = M_{0c} + \rho_c(M_w f_{c \rightarrow w} + M_f f_{c \rightarrow f})$$

$$M_w = M_{0w} + \rho_w(M_c f_{w \rightarrow c} + M_w f_{w \rightarrow w} + M_f f_{w \rightarrow f})$$

$$M_f = M_{0f} + \rho_f(M_c f_{f \rightarrow c} + M_w f_{f \rightarrow w})$$

where

$M_c$  = final ceiling exitance,

$M_w$  = final wall exitance,

$M_f$  = final floor exitance,

$M_{0c}$  = initial ceiling exitance,

$M_{0w}$  = initial wall exitance,

$M_{0f}$  = initial floor exitance,

$\rho_c$  = ceiling reflectance,

$\rho_w$  = wall reflectance,

$\rho_f$  = floor reflectance,

$f_{f \rightarrow c}$  = form factor from the floor to the ceiling,

$f_{f \rightarrow w}$  = form factor from the floor to the walls,

$f_{w \rightarrow c}$  = form factor from the walls to the ceiling,

$f_{w \rightarrow w}$  = form factor from the walls to the walls,

$f_{w \rightarrow f}$  = form factor from the walls to the floor,

$f_{c \rightarrow w}$  = form factor from the ceiling to the walls,

$f_{c \rightarrow f}$  = form factor from the ceiling to the floor.

As discussed above, reciprocity between radiative exchange form factors and the simple geometry of the three-surface model permits six of the seven form factors to be calculated from the single form factor  $f_{f \rightarrow c}$  the radiative exchange form factor between floor and ceiling. This is the fraction of flux leaving the ceiling that reaches the floor directly.  $f_{f \rightarrow c}$  is calculated using the equation for identical, parallel, directly opposed rectangles.

The initial exitances  $M_{0c}$ ,  $M_{0w}$ , and  $M_{0f}$  are determined from

$$M = \frac{\Phi_{\text{onto}} \rho}{\text{area}}$$

where  $\Phi_{\text{onto}}$  is in this case, the flux directly from the skylights onto the surface.

The three simultaneous equations can then be solved for the final exitances  $M_c$ ,  $M_w$ , and  $M_f$ . Finally, the illuminance produced at the desk by the ceiling and walls is calculated from



$$E = M_c c_{c \rightarrow p} + M_w c_{p \rightarrow w}$$

where

$c_{c \rightarrow p}$  = configuration factor from the ceiling to the point,

$c_{p \rightarrow w}$  = configuration factor from the walls to the point.

In this case the configuration factor is for a rectangle to a point in a plane parallel to the plane of the rectangle. This equation is found in [Figure 9-3](#).

Since the sum of the configuration factors from all the surfaces enclosing a point is 1.0,

$$c_{p \rightarrow w} = 1.0 - c_{c \rightarrow p}$$

**6. Solve the Equations.** The radiative exchange form factor between floor and ceiling,  $f_{f \rightarrow c}$  is calculated using [Figure 9-5](#). Substituting the dimensions determined in step 1 into the appropriate equation, it is determined that  $f_{f \rightarrow c} = 0.52571$ .

We now use the relationships among the other form factors (from Equations 9-28 through 9-31):

$$\begin{aligned} f_{c \rightarrow f} &= f_{f \rightarrow c} = 0.52571, \\ f_{c \rightarrow w} &= f_{f \rightarrow w} = 1 - f_{c \rightarrow f} = 0.47429, \\ f_{w \rightarrow c} &= f_{w \rightarrow f} = \frac{A_c}{A_w} (1 - f_{c \rightarrow f}) = 0.33200, \\ f_{w \rightarrow w} &= 1 - 2f_{w \rightarrow c} = 0.33599, \end{aligned}$$

where  $A_c$  is the area of the ceiling and  $A_w$  is the area of the walls. The equations for  $M_c$ ,  $M_w$ , and  $M_f$  become

$$\begin{aligned} M_c &= M_{0c} + 0.80(M_w 0.47429 + M_f 0.52571), \\ M_w &= M_{0w} + 0.46(M_c 0.33200 + M_w 0.33599 + M_f 0.33200), \\ M_f &= M_{0f} + 0.20(M_c 0.52571 + M_w 0.47429). \end{aligned}$$

The initial exitance of the ceiling,  $M_{0c}$ , is zero, since the skylights cannot directly illuminate the ceiling:  $M_{0c} = 0.0$ . The initial exitance of the floor,  $M_{0f}$  is given by

$$M_{0f} = \frac{\Phi_{\text{skylights} \rightarrow \text{floor}} \rho_f}{A_f}$$

where

$\Phi_{\text{skylights} \rightarrow \text{floor}}$  = flux emitted by the skylights that reaches the floor directly,  
 $A_f$  = area of the floor.

The flux from the skylights to the floor is calculated from the total flux leaving the skylights and the radiative exchange form factors from the skylights to the floor:

$$\Phi_{\text{skylights} \rightarrow \text{floor}} = \sum_{i=1}^4 \Phi_{\text{skylight}_i} f_{\text{skylight}_i \rightarrow \text{floor}}$$

The summation is over the four skylights in the room. Since the skylights are identical and placed symmetrically with respect to the calculation point and the center of the room, each emits the same number of lumens, and the form factors from each skylight to the floor are identical. Thus

$$\Phi_{\text{skylights} \rightarrow \text{floor}} = 4 \Phi_{\text{skylight}} f_{\text{skylight} \rightarrow \text{floor}}$$

$\Phi_{\text{skylight}}$  is calculated from  $\Phi_{\text{skylight}} = M_{\text{skylight}} A_{\text{skylight}}$ . Thus

$$M_{of} = \frac{4 M_{\text{skylight}} A_{\text{skylight}} f_{\text{skylight} \rightarrow \text{floor}} \rho_f}{A_f}$$

The skylight exitance  $M_{\text{skylight}}$ , as calculated in example 4, is 2057 lm/ft<sup>2</sup>. The radiative exchange form factor from a skylight to the floor is calculated from the appropriate equation in [Figure 9-6](#). The resulting value of  $f_{\text{skylight} \rightarrow \text{floor}}$  is 0.556. Solving for  $M_{of}$  then, we have

$$M_{of} = \frac{4(2057)(16)(0.556)(0.20)}{(28)(28)} = 18.7 \frac{\text{lm}}{\text{ft}^2}$$

The initial wall exitance is treated similarly:

$$M_{ow} = \frac{4 M_{\text{skylight}} A_{\text{skylight}} f_{\text{skylight} \rightarrow \text{walls}} \rho_w}{A_w}$$

The radiative exchange form factor from the skylight to the walls is found by closure; that is, all of the flux emitted by a skylight that does not reach the floor must reach the walls:  $f_{\text{skylight} \rightarrow \text{walls}} = 1 - f_{\text{skylight} \rightarrow \text{floor}} = 1 - 0.556 = 0.444$ . Thus

$$M = \frac{4(2057)(16)(0.444)(0.50)}{(4)(28)(10)} = 26.1 \frac{\text{lm}}{\text{ft}^2}$$

With these three values of initial exitance, the three simultaneous equations become

$$\begin{aligned} M_w &= 26.1 + M_c 0.15372 + M_w 0.15556 + M_f 0.15372 \\ M_f &= 18.7 + M_c 0.10514 + M_w 0.09486 \\ M_c &= 0.0 + M_w 0.37943 + M_f 0.42057 \end{aligned}$$

The solution of these three equations yields  $M_c = 25.87 \text{ lm/ft}^2$ ,  $M_w = 40.21 \text{ lm/ft}^2$ , and  $M_f = 25.23 \text{ lm/ft}^2$ .

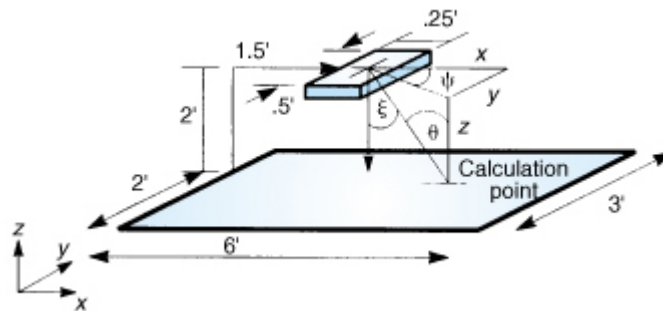
The configuration factor from the calculation point to the ceiling,  $c_{c \rightarrow p}$ , is calculated as described in [Figure 9-2](#). Its value is 0.811. By closure, the configuration factor from the calculation point to the walls,  $c_{p \rightarrow w}$ , equals  $1.0 - c_{c \rightarrow p} = 0.189$ . Finally, solving for the interreflected illuminance  $E$ , we have  $E = M_c c_{c \rightarrow p} + M_w c_{p \rightarrow w} = 25.87(0.811) + 40.21(0.189) = 28.76 \text{ fc}$ .

The sum of the direct (from example 4) and interreflected illuminance components is  $E_{\text{total}} = 86 + 28.76 = 115 \text{ fc}$ . Thus the calculated value for the illuminance is 115 fc for the prescribed time, location, and sky.

## Example 6: Calculation of Luminances Produced by a Point Source

This example illustrates the task lighting analysis of a desk. A small desk luminaire is to be used for lighting desks in workstations ([Figure 9-51](#)).

**1. Determine the Quantity to be Calculated.** The analysis of the performance of a task light on a desk consists, in part, of a determination of the luminance of a white piece of paper.



**Figure 9-51.** Desk layout for Example 6.

**2. Identify Luminaires and the Information Describing Them.** The luminaire used is a single 13-W compact fluorescent lamp with a reflector that produces a very directional luminous intensity distribution. The luminaire is 6 in. long, 3 in. wide, and 1.5 in. high. It is mounted on a movable arm designed to permit it to be placed off to the side of the desk. The photometric data are shown in [Figure 9-52](#).

| Elevation<br>Angle $\theta$ | Intensity (cd) at Azimuthal Angle $\psi$ |       |       |       |       |
|-----------------------------|------------------------------------------|-------|-------|-------|-------|
|                             | 0.0°                                     | 22.5° | 45.0° | 67.5° | 90.0° |

|       |     |     |     |     |     |
|-------|-----|-----|-----|-----|-----|
| 0.0°  | 450 | 450 | 450 | 450 | 450 |
| 5.0°  | 453 | 457 | 453 | 445 | 442 |
| 15.0° | 437 | 446 | 450 | 454 | 451 |
| 25.0° | 406 | 422 | 447 | 470 | 478 |
| 35.0° | 362 | 391 | 443 | 497 | 523 |
| 45.0° | 302 | 350 | 448 | 551 | 592 |
| 55.0° | 233 | 310 | 474 | 624 | 678 |
| 65.0° | 158 | 284 | 505 | 651 | 691 |
| 75.0° | 81  | 263 | 432 | 529 | 559 |
| 85.0° | 20  | 134 | 178 | 192 | 193 |
| 90.0° | 1   | 4   | 5   | 8   | 10  |

**Figure 9-52.** Luminous Intensity Distribution of Desk Luminaire

**3. Determine the Accuracy, Complexity, and Detail of the Calculation.** The luminance of the paper is assumed to be diffuse, so the luminance calculation requires only a determination of the illuminance and a measurement of the paper's diffuse reflectance.

As shown in [Figure 9-51](#), the luminaire arm is mounted at the side of a desk whose dimensions are 6 × 3 ft. The luminaire is located at a height of 2 ft above the desk surface, 1.5 ft to the left of the center of the desk, and 2 ft from the front of the desk. The distance from the center of the luminaire to the center of the desk is given by

$$D = \sqrt{x^2 + y^2 + z^2} = \sqrt{1.5^2 + 0.5^2 + 2^2} = 2.55 \text{ ft}$$

This distance is larger than 5 times the maximum luminous dimension of the luminaire (0.5 ft), so the inverse square cosine law for the illuminance from a point source can be used.

**4. Identify Required Geometric, Reflectance, and Ancillary Data.** The geometric dimensions are shown in [Figure 9-51](#). The white paper is a diffusely reflecting object with a reflectance  $\rho = 0.83$ .

**5. Determine Appropriate Equations.** The luminance ( $L$ ) of a diffusely reflecting surface is given by the following formula:

$$L = \frac{M}{\pi} = \frac{\rho_{\text{paper}} E}{\pi}$$

The illuminance at the center of the desk is given by

$$E = \frac{I(\theta, \psi) \cos \theta}{D^2}$$

The luminous intensity distribution data are shown in [Figure 9-52](#). The angles required to determine the luminous intensity are calculated as follows from geometric principles ([Figure 9-](#)

51):

$$\theta = \arctan \left( \frac{\sqrt{x^2 + y^2}}{z} \right)$$

$$\psi = \arctan \left( \frac{y}{x} \right)$$

$$\xi = \arctan \left( \frac{\sqrt{x^2 + y^2}}{z} \right)$$

**6. Solve the Equations.** First, the illuminance produced by the luminaire is calculated. Using the dimensions in [Figure 9-51](#),

$$\theta = \arctan \left( \frac{\sqrt{1.5^2 + 0.5^2}}{2} \right) = 38.3^\circ$$

$$\psi = \arctan \left( \frac{0.5}{1.5} \right) = 18.4^\circ$$

Linearly interpolating in the table of luminous intensities ([Figure 9-52](#)), the intensity at ( $\theta = 38.3^\circ$ ,  $\psi = 18.4^\circ$ ) has a value of 356 cd.

The incident angle is given by

$$\xi = \arctan \left( \frac{\sqrt{1.5^2 + 0.5^2}}{2} \right) = 38.3^\circ$$

The illuminance  $E$  is calculated as follows:

$$E = \frac{I(\theta, \psi) \cos \theta}{D^2} = \frac{356 \cos (38.3^\circ)}{1.5^2 + 0.5^2 + 2^2} = 42.9 \text{ fc}$$

The luminance of the paper is

$$L_{\text{paper}} = \frac{\rho_{\text{paper}} E}{\pi} = \frac{(0.83) (42.9)}{\pi} = 11.4 \text{ cd / ft}^2$$

## 7: Calculation of Contrast Produced on Printed Material

This example also illustrates the task lighting analysis of a desk. A small desk luminaire is to be used for task lighting desks in workstations.

**1. Determine the Quantity to be Calculated.** The analysis of the performance of a task light on a desk consists, in part, of a determination of the visual task contrast that is produced on the

horizontal desk surface. The contrast determined here is that for black print on white glossy paper, such as is commonly found in journals and magazines.

**2. Identify Luminaires and the Information Describing Them.** The same luminaire is used for this example was for Example 6. The luminous intensity distribution is shown in [Figure 9-52](#).

**3. Determine the Accuracy, Complexity, and Detail of the Calculation.** Calculating the contrast requires determining the luminance of both the task and its background. Neither the paper nor the print ink is assumed to have a diffuse reflectance for this example. Therefore, the calculation of these luminances requires both the illuminance and the bidirectional reflectance distribution function (BRDF) of the task and its background.

The layout of the task is shown in [Figure 9-53](#). As calculated in Example 6, the distance from the task (at the center of the desk) to the center of the luminaire is 2.55 ft, which is larger than 5 times the maximum luminous dimension of the luminaire. Thus the inverse square cosine law is valid in this case.

**4. Identify Required Geometric, Reflectance, and Ancillary Data.** The necessary dimensions are shown in the figure. The BRDFs for the paper and for the printed ink are shown in [Figures 9-54](#) and [9-55](#), for a typical viewing angle of 10° from vertical. The irregular spacing of the azimuth and declination angles in the BRDF tables reflects the degree of specularity for the material. Where angles are spaced closer together, the BRDF is more sensitive to small changes in these angles.

**5. Determine Appropriate Equations.** The luminance contrast  $C$  of a task is given by

$$C = \frac{|L_b - L_t|}{L_b}$$

where  $L_b$  is the luminance of the background and  $L_t$  is the luminance of the target. In this example, the luminances are of nondiffusely reflecting surfaces. The luminance of a nondiffusely reflecting surface illuminated by an unpolarized source is described earlier in this chapter, and is

$$L(\theta_v) = \sum_i \sum_j E(\theta_i, \psi_j) f_r(\theta_v; \theta_i, \psi_j)$$

where

$\theta_v$  = viewing declination angle, in this case equal to 10°,

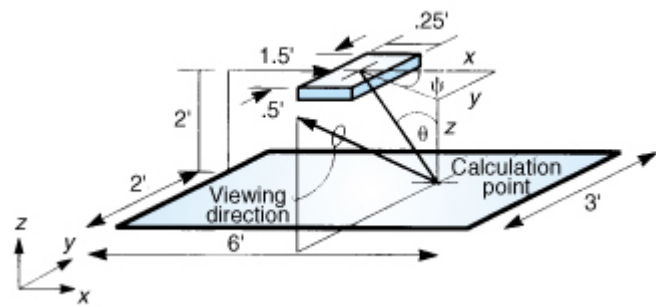
$\theta_i$  = incident declination angle,

$\psi_j$  = incident azimuthal angle, measured from the plane containing the direction of view and

given by  $\psi_j = 90^\circ + \arctan(y/x)$ .

The sum is taken over all the discrete values of illuminance. The number of discrete steps determines the accuracy of the approximation. The step size in these approximations is determined by the need to model high gradients of either the illuminance or the BRDFs. In the present case, the largest declination angle subtended by the luminaire to the calculation point is 6.9°, and the largest azimuthal angle subtended by the luminaire is 19.9°. The azimuthal and declination incident angles from the center of the luminaire are used to determine the region of

the BRDFs being used. Examination of this region reveals whether discretization is necessary for an illuminating field that measures  $6.9^\circ \times 19.9^\circ$ .



**Figure 9-53.** Desk lamp drawing for Example 7.

**6. Solve the Equations.** The illuminance at the center of the desk is 42.9 fc, as shown in example 6. The luminances of task and background require determining the BRDFs of the paper and of the printed ink at the specified angles. The incident azimuthal angle  $\psi_i$  must be determined:  $\psi_i = 90^\circ + \arctan (1.5/0.5) = 161.5^\circ$ .

The incident declination angle has been determined to be  $38.3^\circ$  in Example 6. Given the viewing angle of  $10^\circ$ , the BRDF tables in Figures 9-54 and 9-55 for the paper and ink are interpolated to obtain the values  $f_{\text{ink}}(10^\circ; 38.3^\circ, 161.5^\circ) = 0.0001$  and  $f_{\text{paper}}(10^\circ; 38.3^\circ, 161.5^\circ) = 0.2182$ .

| Azimuth | BRDF (sr <sup>-1</sup> ) at Declination |       |       |       |       |       |
|---------|-----------------------------------------|-------|-------|-------|-------|-------|
|         | 24°                                     | 28°   | 34°   | 44°   | 52°   | 60°   |
| 0°      | 0.226                                   | 0.221 | 0.215 | 0.216 | 0.205 | 0.194 |
| 130°    | 0.240                                   | 0.226 | 0.220 | 0.217 | 0.208 | 0.197 |
| 150°    | 0.249                                   | 0.231 | 0.224 | 0.214 | 0.208 | 0.196 |
| 160°    | 0.252                                   | 0.231 | 0.221 | 0.214 | 0.200 | 0.196 |
| 170°    | 0.253                                   | 0.233 | 0.222 | 0.216 | 0.212 | 0.196 |
| 176°    | 0.250                                   | 0.234 | 0.223 | 0.216 | 0.206 | 0.197 |
| 177°    | 0.261                                   | 0.235 | 0.224 | 0.217 | 0.205 | 0.198 |
| 178°    | 0.262                                   | 0.236 | 0.223 | 0.218 | 0.211 | 0.198 |
| 179°    | 0.263                                   | 0.235 | 0.223 | 0.219 | 0.213 | 0.200 |
| 180°    | 0.263                                   | 0.234 | 0.222 | 0.219 | 0.210 | 0.193 |

\*Viewing declination angle =  $10^\circ$ , viewing azimuth angle =  $0^\circ$ .

**Figure 9-54.** Partial Bidirectional Reflectance Distribution Function (BRDF) Data for White Paper\*

| Azimuth | BRDF (sr <sup>-1</sup> ) at Declination |       |       |       |       |       |
|---------|-----------------------------------------|-------|-------|-------|-------|-------|
|         | 22°                                     | 28°   | 36°   | 44°   | 52°   | 60°   |
| 0°      | 0.004                                   | 0.003 | 0.002 | 0.001 | 0.000 | 0.000 |
| 130°    | 0.013                                   | 0.002 | 0.000 | 0.000 | 0.000 | 0.000 |
| 150°    | 0.034                                   | 0.006 | 0.000 | 0.000 | 0.000 | 0.000 |
| 160°    | 0.056                                   | 0.010 | 0.000 | 0.000 | 0.000 | 0.000 |
| 170°    | 0.089                                   | 0.015 | 0.001 | 0.000 | 0.000 | 0.000 |
| 176°    | 0.109                                   | 0.018 | 0.001 | 0.000 | 0.000 | 0.000 |
| 177°    | 0.111                                   | 0.019 | 0.001 | 0.000 | 0.000 | 0.000 |

|      |       |       |       |       |       |       |
|------|-------|-------|-------|-------|-------|-------|
| 178° | 0.113 | 0.019 | 0.002 | 0.000 | 0.000 | 0.000 |
| 179° | 0.116 | 0.020 | 0.002 | 0.000 | 0.000 | 0.000 |
| 180° | 0.118 | 0.020 | 0.002 | 0.000 | 0.000 | 0.000 |

\*Viewing declination angle = 10°, viewing azimuth angle = 0°.

**Figure 9-55.** Partial BRDF Data for Black Printed Ink\*

The units of BRDFs are inverse steradians ( $\text{sr}^{-1}$ ). The luminance of the ink at the calculation point is then  $L_{\text{ink}} = E(\theta_{\dot{p}} \psi_{\dot{p}}) f_r(\theta_{\dot{v}}; \theta_{\dot{p}} \psi_{\dot{p}}) = (42.9 \text{ fc})(0.0001 \text{ sr}^{-1}) = 0.0043 \text{ cd/ft}^2$ . The luminance of the paper at the calculation point is  $L_{\text{paper}} = E(\theta_{\dot{p}} \psi_{\dot{p}}) f_r(\theta_{\dot{v}}; \theta_{\dot{p}} \psi_{\dot{p}}) = (42.9 \text{ fc})(0.2182 \text{ sr}^{-1}) = 9.36 \text{ cd/ft}^2$ . The luminance contrast of the task and background is then

$$C = \frac{|9.36 - 0.0034|}{9.36} = 0.999$$

Calculations of contrast for the extreme azimuth and declination angles subtended by the luminaire result in the following contrasts at the calculation point:

$$\begin{aligned} C(38.3^\circ + 3.45^\circ, 161.5^\circ + 9.95^\circ) &= C(41.75^\circ, 171.45^\circ) = 0.999 \\ C(38.3^\circ + 3.45^\circ, 161.5^\circ - 9.95^\circ) &= C(41.75^\circ, 151.55^\circ) = 1.000 \\ C(38.3^\circ - 3.45^\circ, 161.5^\circ + 9.95^\circ) &= C(34.85^\circ, 171.45^\circ) = 0.986 \\ C(38.3^\circ - 3.45^\circ, 161.5^\circ - 9.95^\circ) &= C(34.85^\circ, 151.55^\circ) = 0.970 \end{aligned}$$

Each of these lies within 10% of the contrast calculated using a single point at the center of the luminaire, so discretization of the luminaire into several elements is not required.

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